Modelling Airport Surface Safety: A Framework For A Holistic Airport Safety Management

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Declaration of Originality

I hereby declare that I have personally carried out the entire work described in this thesis. Where sources of information or the work of others have been used, they are fully cited and referenced and / or with appropriate acknowledgement given.



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Sabine Wilke

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Abstract

Airports are complex systems involving the continuous interaction of human operators with the physical infrastructure, technology and procedures to ensure the safe and efficient conduct of flights. From an operational perspective, airport surface operations (i.e. runway and taxiway operations) require the interaction of five main stakeholders (i.e. crew or pilots, air traffic control, airport operator, ground handling and regulator) both to facilitate the ground movement of aircraft and vehicles, and to maintain the surface in a working condition. The complexity of these operations makes the runway and taxiway system vulnerable and presents a risk of failure with the consequent potential for the occurrence of accidents. Therefore, the development and implementation of an effective Safety Management System (SMS) are required to ensure the highest level of safety for surface operations.

A SMS is a systematic approach to managing safety based on the four cornerstones of safety policy and objectives, risk management, assurance, and safety promotion. Although the International Civil Aviation Organisation (ICAO) provides the global legislative framework for SMS, the relevant regulations are still to be established at the national level with the consequence that practical guidance on the development and implementation of SMS is rare, and reliable tools to support SMS are lacking. The consequence of this is that the current approach to surface safety management is piecemeal and not integrated. Typically, a single accident and incident type is investigated from the perspective of an individual stakeholder with the consequence that resulting proposals for safety mitigation measures are biased and limited in terms of their impact. In addition, the industry is characterised by non-standardised data collection and investigation practices, insufficient or missing definitions, differing reporting levels, and a lack of a coherent and standardised structure for efficient coding and analysis of safety data. Since these shortcomings are a

major barrier to the required holistic and integrated approach to safety management, this thesis addresses the four cornerstones of SMS and recommends major enhancements. In particular, a framework for a holistic airport surface safety management is proposed. The framework comprises the static airport architecture, a process model of surface operations, the determination of causal factors underlying failure modes of these operations, a macroscopic scenario tool and a functional relationship model. Safety data and other data sources feed the framework and a dedicated data pre-processing strategy ensures its validity.

Unlike current airport surface safety management practices, the proposed framework assesses the safety of the operations of all relevant actors. Firstly, the airport architecture is modelled and the physical and functional variability of airports defined. Secondly, a process model of surface operations is developed, which captures the tasks of the stakeholders and their interactions with physical airport surface infrastructure. This model serves as a baseline model and guides the further development of the airport SMS. To manage the safety of surface operations, the causes of accidents and incidents must be identified and their impacts understood. To do so, a reference data set combining twelve databases from airlines, airport operators, Air Navigation Service Providers (ANSPs), ground handling companies and regulators is collected. Prior to its analysis, the data is assessed for its quality, and in particular, for its internal validity (i.e. precision), external validity (i.e. accuracy) and in terms of reporting levels. A novel external data validation framework is developed and each database is rated with a data quality index (DQI). In addition, recommendations for reporting systems and safety policies are given. Subsequently, the data is analysed for causal factors across stakeholders and the contribution of the individual actors are highlighted. For example, the analysis shows that the various stakeholders capture different occurrence types and underlying causal factors, often including information that is of potential use for another party. The analysis is complemented by interviews, observations and statistical analysis, and the results are summarised in a new taxonomy. This taxonomy is applicable to all relevant stakeholders and is recommended for operational safety risk management. After the airport surface operations have been modelled and the drivers to safety identified, the results are combined, resulting in a macroscopic scenario tool which supports the management of change (i.e. safety assurance), training and education, and safety communication (i.e. safety promotion) functions of the SMS. Finally, a structured framework to assess the functional relationship between airport surface accidents / incidents and their underlying

causal factors is proposed and the system is quantified in terms of safety. Compared to the state-of-the-art safety assessments that are biased and limited in terms of their impact, the holistic approach to surface safety allows modelling the safety impact of each system component, their interactions and the entire airport surface system architecture.

The framework for a holistic airport surface safety management developed in this thesis delivers a SMS standard for airports. The standard exceeds international requirements by standardizing the two SMS core functions (safety risk management and safety assurance) and integrating safety-relevant information across all relevant stakeholders. This allows a more effective use of safety information and provides an improved overview on, and prediction of, safety risks and ultimately improves the safety level of airports and their stakeholders. Furthermore, the methodology employed in this thesis is flexible and could be applied to all aspects of aviation SMS and system analysis.

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Table of Contents

List of Figures 19
List of Tables 24
List of Abbreviations 27
1 Introduction 36
1.1 Background 36
1.2 Aim and Objectives 40
1.3 Thesis outline 41
2 The Airport System 44
2.1 Airports and their Function in the Air Transport System 44
2.2 System Architecture 45
2.2.1 Airport Components 45
2.2.2 Airport Operations 46
2.2.3 Key Actors or Stakeholders 49
2.2.3.1 Airport Operator 49
2.2.3.2 Airlines 49
2.2.3.3 Ground Handling Companies 50
2.2.3.4 Air Navigation Service Providers 51
2.2.3.5 Contractors 51
2.2.3.6 Regulators 51
2.2.3.7 External Stakeholders 52
2.2.4 Airport Heterogeneity 54
2.3 Surface Operations 61
2.4 Key Performance Indicators 63
2.4.1 Airport Performance Measurement 63

2.4.2 The Importance of Safety 66
2.5 Airport Surface Safety 66
2.6 Summary 68
3 Airport Surface Operations 69
3.1 Methodology 70
3.1.1 Business Process Modelling 70
3.1.2 Unified Modelling Language 71
3.1.3 Method for Derivation of a Business Process Model 73
3.1.4 Implementation of the Method 77
3.2 Process Model of Normal Airport Surface Operations 80
3.2.1 Terminology 80
3.2.2 Physical Infrastructure 81
3.2.3 Airport Authority Model 84
3.2.4 Pilot Model 85
3.2.4.1 High-level Task Analysis 86
3.2.4.2 Hierarchical Task Analysis 87
3.2.4.3 Actors 91
3.2.5 Vehicle Driver / Pedestrian Model 91
3.2.5.1 High-level Task Analysis 92
3.2.5.2 Hierarchical Task Analysis 93
3.2.5.3 Actors 96
3.2.6 ATC Model 98
3.2.6.1 High-level Task Analysis 100
3.2.6.2 Hierarchical Task Analysis 100
3.2.6.3 Actors 101
3.2.7 Regulatory Model 102
3.2.8 Interfaces 103
3.2.9 The Airport Surface System 103
3.3 Time Effects 105
3.3.1 Methodology 106
3.3.2 Results 107
3.3.2.1 Pilot Model 108
3.3.2.2 Vehicle Driver / Pedestrian Model – Airport Authority 109
3.3.2.3 Vehicle Driver / Pedestrian Model – Ground Handling 110

3.3.2.4 ATC Model 110
3.3.2.5 Duration of Time Effects 110
3.3.2.6 System Effects 111
3.4 Summary 114
4 Airport Safety Management 115
4.1 Fundamentals of Safety Management 115
4.2 State Safety Programme 119
4.2.1 Safety Measures 119
4.2.2 Accidents and Incidents 120
4.3 Safety Management Systems 121
4.3.1 Concept and Regulatory Anchoring 122
4.3.2 ICAO SMS Framework 123
4.3.2.1 SMS Prerequisites 125
4.3.2.2 Safety Policy and Objectives 125
4.3.2.3 Safety Risk Management 126
4.3.2.4 Safety Assurance 127
4.3.2.5 Safety Promotion 128
4.3.2.6 The Importance of Safety Data 130
4.4 Airport SMS 132
4.5 Airport Surface Safety 134
4.5.1 Excursions 134
4.5.2 Ground Collisions 138
4.5.3 Incursions 141
4.5.4 Foreign Object Damage 142
4.5.5 Wildlife Strikes 143
4.5.6 Interactions 145
4.6 Summary 146
5 Airport Safety Modelling 147
5.1 Failure Modes of Airport Surface Operations 147
5.2 Airport Surface Safety Modelling – State-of-the-Art 150
5.2.1 Method for Reviewing the Literature 150
5.2.2 Incursions / Ground Collisions 155
5.2.2.1 Causal Factors 156
5.2.2.2 Analytical Methodologies and Data Quality Issues 160

5.2.2.3 Safety Risk Mitigation Strategies 163
5.2.3 Excursions 166
5.2.3.1 Causal Factors 168
5.2.3.2 Analytical Methodologies and Data Quality Issues 172
5.2.3.3 Safety Risk Mitigation Strategies 175
5.2.4 FOD 177
5.2.4.1 Causal Factors 178
5.2.4.2 Analytical Methodologies and Data Quality Issues 179
5.2.4.3 Safety Risk Mitigation Strategies 180
5.2.5 Wildlife Strikes 182
5.2.5.1 Causal Factors 183
5.2.5.2 Analytical Methodologies and Data Quality Issues 185
5.2.5.3 Safety Risk Mitigation Strategies 186
5.2.6 Initial Taxonomy of Causal Factors Underlying Airport Surface Safety Occurrences 187
5.2.7 Taxonomies 188
5.2.8 Summary of Findings on Surface Safety Modelling 193
5.3 A Holistic Approach Towards Surface Safety 195
5.4 Summary 197
6 Data Collection and Validation 199
6.1 Data Requirements 200
6.2 Data Selection 201
6.2.1 Traffic Statistics 201
6.2.2 Subject Matter Expert Consultation 203
6.2.3 Matching the Data Requirements 204
6.2.3.1 United States 204
6.2.3.2 United Kingdom 205
6.2.3.3 Norway 205
6.2.3.4 New Zealand 206
6.2.3.5 Data Choice and Quality 206
6.3 Data Availability and Collection 207
6.3.1 United States 208
6.3.2 United Kingdom 209
6.3.3 Norway 210

6.3.4 New Zealand 210
6.4 Data Overview 211
6.5 Data Quality Assessment 212
6.5.1 Data Quality Issues 213
6.5.2 Definitions 215
6.5.3 Data Quality Assessment in Aviation Research 216
6.5.4 Data Validation Framework 216
6.5.4.1 Internal Data Validation 217
6.5.4.2 External Data Validation 221
6.5.4.3 Reporting Level 236
6.5.4.4 Discussion 239
6.5.5 Conclusions Data Quality Assessment 243
6.6 Database Introduction and Data Pre-Processing 244
6.6.1 FAA RI Database 245
6.6.2 FAA AIDS 246
6.6.3 Signature SHEBBA 246
6.6.4 UK CAA MORS 247
6.6.5 easyJet AQD 248
6.6.6 CAA Norway ECCAIRS 249
6.6.7 Avinor ANSP MESYS 250
6.6.8 Avinor Airports MESYS 251
6.6.9 OSL IFS 252
6.6.10 Norwegian AQD 253
6.6.11 Wideroe Sentinel 253
6.6.12 CAA NZ ASMS 254
6.7 Data Coding and Validation 255
6.8 Refined Taxonomy of Causal Factors Underlying Airport Surface Safety Occurrences 257
6.9 Summary 259
7 Analysis of Causal Factors 260
7.1 Methodology 260
7.2 United States 264
7.2.1 Data Overview 264
7.2.2 Occurrence Rates 264

7.2.3 Frequency Analysis 266
7.2.4 Comparison of Stakeholder Viewpoints 272
7.2.5 Examination of Relationships 273
7.2.6 Interviews 276
7.2.7 Wildlife Analysis 280
7.2.8 Conclusions United States 282
7.3 United Kingdom 283
7.3.1 Data Overview 283
7.3.2 Occurrence Rates 283
7.3.3 Frequency Analysis 286
7.3.4 Comparison of Stakeholder Viewpoints 293
7.3.5 Examination of Relationships 294
7.3.6 Conclusions United Kingdom 297
7.4 Norway 298
7.4.1 Data Overview 298
7.4.2 Occurrence Rates 299
7.4.3 Frequency Analysis 302
7.4.4 Comparison of Stakeholder Viewpoints 311
7.4.5 Examination of Relationships 316
7.4.6 Conclusions Norway 319
7.5 New Zealand 320
7.5.1 Data Overview 320
7.5.2 Occurrence Rates 320
7.5.3 Frequency Analysis 320
7.5.4 Examination of Relationships 323
7.5.5 Wildlife Analysis 324
7.5.6 Conclusions New Zealand 324
7.6 Discussion 325
7.7 Summary 327
8 Cross-State Analysis 328
8.1 Cross-Stakeholder Comparison 328
8.1.1 Frequency Analysis 329
8.1.2 Data Detail 333
8.1.3 Contribution of Individual Stakeholders 333

8.1.4 Examination of Relationships....336
8.2 Cross-Occurrence Analysis....339
8.2.1 Relationships Between Occurrence Types....339
8.2.2 Shared Causal Factors....342
8.3 Discussion....342
8.4 Stochastic Elements in the Airport Surface System....344
8.5 Summary....349
9 A Macroscopic Scenario Tool for Airport SMS....350
9.1 Process Model of Airport Surface Operations....351
9.1.1 Methodology....351
9.1.2 Baseline Model for Airport SMS....352
9.1.3 Application....352
9.2 A New Taxonomy of Causal Factors Underlying Airport Surface Safety Occurrences....354
9.2.1 Methodology....354
9.2.1.1 Taxonomy Development....354
9.2.1.2 Taxonomy Validation....355
9.2.2 Validation and Reliability Checks....363
9.2.2.1 Reliability....363
9.2.2.2 Construct Validity....365
9.2.2.3 Content Validity....365
9.2.2.4 Criterion Validity....367
9.2.2.5 External Validation....367
9.2.3 Taxonomy Structure....367
9.2.4 Comparison to Existing Taxonomies....368
9.2.5 Application, Transferability and Limitations....371
9.3 Macroscopic Scenario Tool....372
9.3.1 Introduction of the Tool....373
9.3.1.1 Direct Drivers....373
9.3.1.2 Indirect Drivers....374
9.3.1.3 Stochastic Drivers....377
9.3.1.4 Other Drivers....378
9.3.2 Application of the Tool....380
9.4 Summary....382

10 The Impact of Airport Characteristics 384
10.1 Background 385
10.2 Methodology 386
10.2.1 Safety Data 388
10.2.2 Airport Characteristics and Measurement Variables 388
10.2.3 Sampling 394
10.2.4 Survey Methodology 394
10.2.5 Questionnaire Design 396
10.2.6 Pilot Survey 397
10.2.7 Full Survey 397
10.2.8 Aeronautical Information Publication and Aeronautical Databases 397
10.2.9 Potential Sources of Error 399
10.2.10 Data Analysis 399
10.2.10.1 High-level Analysis and Sample Characteristics 399
10.2.10.2 Data Distribution 400
10.2.10.3 Data Homogeneity 400
10.2.10.4 Analysis for Associations 400
10.3 Results and Discussion 403
10.3.1 High-level Analysis and Sample Characteristics 404
10.3.1.1 Safety Data 404
10.3.1.2 Airport Location 407
10.3.1.3 Traffic Characteristics 408
10.3.1.4 Manoeuvring Area Characteristics 408
10.3.1.5 Equipment and Installations 411
10.3.1.6 Visual Navigation Aids 412
10.3.1.7 Airfield Operations and Maintenance 412
10.3.1.8 Regulations 413
10.3.1.9 Human Resources 414
10.3.1.10 Outliers 414
10.3.2 Data Distribution 415
10.3.3 Data Homogeneity 415
10.3.4 Analysis for Associations 417
10.3.4.1 Results 418
10.3.4.2 Discussion 420

10.4 Summary 422
11 Airport Surface Safety Model 423
11.1 Methodology 424
11.1.1 Modelling Objective 424
11.1.2 Data Choice and Distribution 424
11.1.2.1 Runway Incursion Severity Classification 425
11.1.2.2 Distribution of Severity Categories 426
11.1.2.3 Distribution of Causal Factors 427
11.1.2.4 Distribution of Airport Characteristics 427
11.1.3 Model Choice 427
11.1.4 Modelling Strategy 429
11.2 Results 436
11.2.1 High-level Analysis of Causal Factors 436
11.2.2 Analysis of Individual Groups of Causal Factors 437
11.2.2.1 Air Traffic Control 437
11.2.2.2 Pilot 440
11.2.2.3 Vehicle Driver / Pedestrian 443
11.2.2.4 Airport Characteristics 444
11.2.3 Analysis of Interactions 453
11.2.3.1 Interaction of Human-Related Factors 453
11.2.3.2 Influence of Airport Characteristics on Surface Operations 454
11.3 Discussion 459
11.4 Recommendations 461
11.5 Framework for a Holistic Airport Safety Management 463
11.6 Summary 465
12 Discussion and Future Work 466
12.1 Revisiting the Research Objectives 466
12.2 Conclusions 467
12.2.1 Model of the Functional Architecture of Airports 467
12.2.2 Development of a 4D Process Model 468
12.2.3 Review of the Literature and Current Airport Surface Safety Analysis and Mitigation Practices 468
12.2.4 Development of a Data Validation Framework 468
12.2.5 Determination of Causal Factors 469

12.2.6 Development of a Macroscopic Scenario Tool 469
12.2.7 Functional Analysis of Airport Surface Safety 469
12.3 Future Work 470
12.4 Publications Relating to this Work 471
12.4.1 Publication Format: Journal – Published 471
12.4.2 Publication Format: Conference Proceedings – Published 472
References 473
Appendix I: Unified Modelling Language 495
Appendix II: Literature Overview 505
Appendix III: Semi-Structured Interview Questions 528
Appendix IV: Evaluation of MCDA Techniques 530
Appendix V: Analysis of Causal Factors - Supplementary Analysis 543
Appendix VI: Final Taxonomy 555
Appendix VII: Questionnaire Survey 579
Appendix VIII: Supplementary Analysis to Chapter 10 585
Appendix IX: Fundamentals of Logistic Regression 622
Appendix X: Supplementary Analysis to Chapter 11 630

List of Figures

Figure 1: Overview of thesis structure....43
Figure 2: Physical and functional architecture of airports....48
Figure 3: Air transport system....52
Figure 4: Components LAX....56
Figure 5: Components LPL....57
Figure 6: Components BOO....58
Figure 7: Airport surface....61
Figure 8: Airport surface actors....62
Figure 9: UML, BPMN, SysML notations for activity flows....72
Figure 10: Methodology for the development of a process model of airport surface operations....79
Figure 11: Airport surface operations - terminology....80
Figure 12: Airport surface infrastructure....83
Figure 13: Tasks airport authority....85
Figure 14: Flight phases....86
Figure 15: Aircraft state diagram....86
Figure 16: Outline activity model - pilot....87
Figure 17: Actors in contact with pilots....91
Figure 18: V/PD operational phases....92
Figure 19: V/PD state diagram....93
Figure 20: Outline activity model –V/PD....93
Figure 21: Actors in contact with V/PD....96
Figure 22: Ground handling actors....98
Figure 23: ATC operational phases....100

Figure 24: Normal ATC operations 101
Figure 25: Actors ATC 102
Figure 26: Tasks regulator 102
Figure 27: Interfaces 103
Figure 28: Airport surface system architecture 104
Figure 29: Relationship between SSP and SMS 122
Figure 30: ICAO SMS framework 124
Figure 31: The safety data cycle 130
Figure 32: Runway excursion Denver 2008 135
Figure 33: Runway excursion Munich 2011 135
Figure 34: Taxiway excursion Atlanta 2012 136
Figure 35: Linate airport disaster 2001 139
Figure 36: Wreckage at Linate airport 2001 139
Figure 37: Concorde crash 2000 142
Figure 38: Bird hazard I 143
Figure 39: Bird hazard II 143
Figure 40: Hudson River crash 2009 I 144
Figure 41: Hudson River crash 2009 II 144
Figure 42: Interaction of occurrences 145
Figure 43: Potential process failures of the airport authority's operation 148
Figure 44: Potential process failures of the pilot's operation 149
Figure 45: Distribution of literature per occurrence type 151
Figure 46: Publishing bodies 151
Figure 47: Analytical methodologies 153
Figure 48: Methodology outline for literature review 154
Figure 49: Engineered materials arresting system 176
Figure 50: Causal factors identified through literature search 188
Figure 51: Research outline 196
Figure 52: Global air traffic forecast 2010-2030 – revenue passenger kilometres 202
Figure 53: Global air traffic forecast 2011-2031 – aircraft fleets 202
Figure 54: Lack of effective implementation indicator vs. traffic 207
Figure 55: High-level methodology data quality assessment 217
Figure 56: Final ranking 231

Figure 57: Correlation DQI vs. normalised number of different causal factors extracted per database....235
Figure 58: Number of reported incursions per 100,000 movements....240
Figure 59: Summary data quality assessment framework....242
Figure 60: Refined taxonomy after safety data analysis....258
Figure 61: FAA reported number of incursions (per 100,000 movements)....265
Figure 62: Causal factors (Level 1) per occurrence type U.S.....267
Figure 63: Causal factors (Level 2) per occurrence type U.S.....267
Figure 64: Causal factors (Level 1) per occurrence type per database U.S.....268
Figure 65: Causal factors (Level 2) per occurrence type per database U.S.....269
Figure 66: Factor combinations – stakeholder / component interaction U.S.....271
Figure 67: Factor combinations (Level 2) U.S. 272
Figure 68: Occurrence type per stakeholder U.S.....273
Figure 69: Causal factors (Level 1) per stakeholder U.S.....274
Figure 70: Causal factors (Level 1) per occurrence type U.S.....275
Figure 71: easyJet reported number of occurrences (per 100,000 movements)....284
Figure 72: Causal factors (Level 1) per occurrence type UK....287
Figure 73: Causal factors (Level 2) per occurrence type UK....287
Figure 74: Causal factors (Level 1) per occurrence type per database UK....288
Figure 75: Causal factors (Level 2) per occurrence type per database UK....289
Figure 76: Factor combinations – stakeholder / component interaction UK....291
Figure 77: Factor combinations (Level 2) UK....292
Figure 78: Occurrence type per stakeholder UK....295
Figure 79: Causal factors (Level 1) per stakeholder UK....296
Figure 80: Causal factors (Level 1) per occurrence type UK....296
Figure 81: CAA-Norway reported number of occurrences (per 100,000 movements)....299
Figure 82: Avinor-ANSP reported number of occurrences (per 100,000 movements)....300
Figure 83: Avinor-Airports reported number of occurrences (per 100,000 movements)..301
Figure 84: OSL reported number of occurrences (per 100,000 movements)....301
Figure 85: Causal factors (Level 1) per occurrence type NO....303
Figure 86: Causal factors (Level 2) per occurrence type NO....304
Figure 87: Causal factors (Level 1) per occurrence type per organisation NO....305
Figure 88: Causal factors (Level 2) per occurrence type per organisation NO....306
Figure 89: Factor combinations – stakeholder / component interaction NO....308

Figure 90: Factor combinations (Level 2) NO 309
Figure 91: Number of stakeholders reporting NO 311
Figure 92: National reporting system NO 315
Figure 93: Occurrence type per stakeholder NO 317
Figure 94: Causal factors (Level 1) per stakeholder NO 317
Figure 95: Causal factors (Level 1) per occurrence type NO 318
Figure 96: Causal factors (Level 1) per occurrence type NZ 321
Figure 97: Causal factors (Level 2) per occurrence type NZ 321
Figure 98: Causal factors (Level 1) per occurrence type NZ 323
Figure 99: Occurrence type per stakeholder 337
Figure 100: Causal factors (Level 1) per stakeholder 338
Figure 101: Influence diagram occurrence types 339
Figure 102: Influence diagram of shared causal factors 342
Figure 103: Stochastic elements in the airport surface system architecture 347
Figure 104: Validated airport surface system architecture 353
Figure 105: Methodology for taxonomy development 355
Figure 106: Taxonomy reliability checks (Levels 1-3) UK CAA 358
Figure 107: Methodology of taxonomy validation 362
Figure 108: Reliability checks UK CAA 363
Figure 109: Reliability checks U.S. Western-Pacific Region 364
Figure 110: Reliability checks U.S. Northeast region 364
Figure 111: Construct validity 366
Figure 112: Direct drivers 374
Figure 113: Indirect drivers – interface communication 375
Figure 114: Indirect drivers - interface location 376
Figure 115: Stochastic drivers 378
Figure 116: Macroscopic scenario tool 379
Figure 117: Scenario evaluation new runway 381
Figure 118: Methodology outline 387
Figure 119: Distribution of causal factors 407
Figure 120: Type 2 conflict point (TWY / TWY) 409
Figure 121: Type 3 conflict point (TWY / TWY) 409
Figure 122: Type 4 conflict point (TWY / TWY) 409
Figure 123: Type 5 conflict point (TWY / TWY) 409

Figure 124: Type 6 conflict points (TWY / TWY) 409
Figure 125: Type 7 conflict points (TWY / TWY) 409
Figure 126: Type 8 conflict points (TWY / TWY) 410
Figure 127: Type 6 conflict point (RWY / TWY) 410
Figure 128: Normalised number of incursions (aggregated) vs. number of runways 416
Figure 129: Normalised number of incursions (aggregated) vs. number of taxiway segments 416
Figure 130: Airport surface design elements 432
Figure 131: Framework for the systematic analysis of airport surface safety 434
Figure 132: System quantification 435
Figure 133: Causal factors (Level 2) across severity categories 436
Figure 134: Pilot human-related causal factors (Level 3) across severity categories 440
Figure 135: Severity categories across number of runways 444
Figure 136: Severity categories across number of type 3 RWY / TWY conflict points 444
Figure 137: Severity categories across number of type 4 RWY / TWY conflict points 445
Figure 138: Severity categories across number of type 4 TWY / TWY conflict points 445
Figure 139: Airport diagrams 449
Figure 140: Significant predictors for runway incursion severity 451
Figure 141: Stakeholder interactions across severity categories 453
Figure 142: Runway approach end type 3 RWY / TWY conflict point 455
Figure 143: Framework for a holistic airport safety management 464

List of Tables

Table 1: General airport characteristics 55
Table 2: Activities LAX, LPL, BOO 59
Table 3: Airport KPAs, KPIs, and drivers 65
Table 4: Case study – airport surface infrastructure 84
Table 5: Task analysis – Pilot model 88
Table 6: Task analysis – V/PD model 94
Table 7: Time variant and invariant operations and tasks 108
Table 8: System effects pilot model 111
Table 9: System effects airport authority model 112
Table 10: System effects ATC model 113
Table 11: Probability classification 117
Table 12: Severity classification 117
Table 13: Safety risk assessment matrix 117
Table 14: Safety risk tolerability matrix 118
Table 15: Runway excursion definitions 137
Table 16: Ground collisions definitions 140
Table 17: High-level causal factors for incursions 157
Table 18: High-level causal factors for excursions 171
Table 19: High-level sources of FOD 178
Table 20: High-level causal factors for wildlife strikes 184
Table 21: Taxonomies 189
Table 22: Data requirements 200
Table 23: Data availability and collection 211
Table 24: Data overview 212

Table 25: Completeness of relevant data fields within the occurrence databases 219
Table 26: Criteria scores 224
Table 27: Scoring and ranking 230
Table 28: Reporting level 237
Table 29: Data overview occurrences U.S. 264
Table 30: Data overview causal factors U.S. 266
Table 31: Top 10 causal factors per database U.S. 270
Table 32: Causal factors based on interviews with U.S. pilots 278
Table 33: Correlation coefficients wildlife strike analysis U.S. Northeast 282
Table 34: Data overview occurrences UK 283
Table 35: Data overview causal factors UK 286
Table 36: Top 10 causal factors per database UK 290
Table 37: Wildlife occurrences UK 293
Table 38: Data overview occurrences NO 298
Table 39: Data overview causal factors NO 303
Table 40: Top 10 causal factors per database NO 306
Table 41: Wildlife occurrences NO 310
Table 42: Correlation coefficients wildlife strike analysis NO 310
Table 43: Distribution of reports per stakeholder NO 312
Table 44: Causal factors (Level 1) per stakeholder NO 315
Table 45: Causal factors (Level 1) per occurrence type per stakeholder NO 318
Table 46: Data overview occurrences NZ 320
Table 47: Data overview causal factors NZ 320
Table 48: Top 10 causal factors NZ 322
Table 49: Correlation coefficients wildlife strike analysis NZ 324
Table 50: Summary causal factor analysis 326
Table 51: Stakeholder overview 329
Table 52: Causal factors (Level 2) per stakeholder per occurrence type 331
Table 53: Coding occurrence I 369
Table 54: Coding occurrence II 369
Table 55: Coding occurrence III 370
Table 56: Airport characteristics with potential impact on surface safety 389
Table 57: Measurement variables 391
Table 58: Statistical tests 401

Table 59: Descriptives - occurrence types 405
Table 60: Severity classification U.S. runway incursions 406
Table 61: Severity classification UK 406
Table 62: Severity classification NO 406
Table 63: Descriptives - airport location 407
Table 64: Descriptives - traffic characteristics 408
Table 65: Descriptives - manoeuvring area characteristics 411
Table 66: Descriptives - equipment and installations 412
Table 67: Descriptives - visual navigation aids 412
Table 68: Descriptives - operations and maintenance 413
Table 69: Descriptives - regulations 413
Table 70: Descriptives - human resources 414
Table 71: Summary of significant associations 419
Table 72: Severity distribution U.S. runway incursions Oct 2007 - 2009 426
Table 73: Parameter estimates causal factors (Level 1) vs. severity 437
Table 74: Most frequent ATC factors 438
Table 75: Parameter estimates pilot human-related factors (Level 3) vs. severity I 442
Table 76: Parameter estimates pilot human-related factors (Level 3) vs. severity II 442
Table 77: Parameter estimates pilot human-related factors (Level 3) vs. severity III 442
Table 78: Parameter estimates pilot human-related factors (Level 3) vs. severity IV 442
Table 79: Parameter estimates pilot human-related factors (Level 3) vs. severity V 443
Table 80: Parameter estimates airport characteristics vs. severity 446
Table 81: Parameter estimates airport characteristics level 1 vs. severity 451
Table 82: Parameter estimates airport characteristics level 2 vs. severity 451
Table 83: Parameter estimates airport characteristics level 3 (RWY/RWY conflict points) vs. severity 451
Table 84: Parameter estimates airport characteristics level 3 (RWY / TWY conflict points) vs. severity 452
Table 85: Parameter estimates airport characteristics level 3 (TWY / TWY conflict points) vs. severity 452
Table 86: Parameter estimates airport characteristics level 3 (type 4 conflict points) vs. severity 452
Table 87: Parameter estimates stakeholder interaction vs. severity 454
Table 88: Causal factors per airport location 458

List of Abbreviations

AA	Airport Authority
AAG	Accident Analysis Group
AAIB (UK)	Air Accident Investigation Branch (UK)
AAIB of Singapore	Air Accident Investigation Bureau of Singapore
AAIU	Ireland Air Accident Investigation Unit
AC	Advisory Circular
A/C	Aircraft
ACC	Area Control Centre
ACI	Airports Council International
ACRP	Airport Cooperative Research Program
ACU	Air Conditioning Unit
ADAB	Administrator's Daily Alert Bulletin
ADREP	Accident / Incident Data Reporting
AHP	Analytical Hierarchical Process
AIDS	Accident / Incident Data System
AIP	Aeronautical Information Publication
AIRPROX	Air Proximity Hazard
AIS	Aeronautical Information Service
ALAR	Approach and Landing Accident Reduction
ALARP	As Low as Reasonably Practicable
ALoS	Acceptable Level of Safety
ALS	Approach Lighting System
AMASS	Airport Movement Area Safety System

ANP	Analytical Network Process
ANSP	Air Navigation Service Provider
AOPA	Aircraft Owners and Pilots Association
AOR	Aviation Occurrence Reporting
AOV	Air Traffic Oversight Service
APD	Airport Police Department
APP	Approach Control Unit
AQD	Aviation Safety Database
AR	Arkansas
ARIA	Aerodrome Runway Incursion Assessment
ARTCC	Air Route Traffic Control Center
ASDE-X	Airport Surface Detection Equipment – Model X
ASDE-3	Airport Surface Detection Equipment – Model 3
ASIS	Aviation Safety Information System
A-SMGCS	Advanced Surface Movement Guidance and Control System
ASMS	Aviation Safety Monitoring System
ASRS	Aviation Safety Reporting System
ASU	Air Starter Unit
ATC	Air Traffic Control
ATCT	Air Traffic Control Tower
ATFCM	Air Traffic Flow and Capacity Management
ATIS	Air Traffic Information Service
ATM	Air Traffic Management
ATQA	Air Traffic Quality Assurance
ATSAP	Air Traffic Safety Action Program
ATSB	Australian Transport Safety Bureau
Avinor ANSP	Avinor AS – ANSP Division
Avinor Airports	Avinor AS – Airports Division
AXSL	ASDE-X Safety Logic
AZ	Arizona
BBN	Bayesian Believe Networks
BC	Boarder Control
BEA	Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation

	Civile
BFU	Bundesstelle fuer Flugunfalluntersuchung
BITRE	Bureau of Infrastructure, Transport and Regional Economics
BOM	Bureau of Meteorology
BOO	Bodo Airport
BPM	Business Process Model
BRI	Birdstrike Risk Index
CA	California
CAA	Civil Aviation Authority
CAA Norway	Civil Aviation Authority – Norway
CAA NZ	Civil Aviation Authority of New Zealand
CADORS	Canadian Civil Aviation Occurrence Reporting System
CANSO	Civil Air Navigation Service Organisation
CAST	Commercial Aviation Safety Team
CAT	Category
CATS	Causal Model for Air Transport Safety
CBP	Customs and Boarder Protection
CFIT	Controlled Flight Into Terrain
CIAIAC	Comisión de Investigación de Accidentes e Incidentes de Aviación Civil
CICTT	CAST / ICAO Common Taxonomy Team
CO	Colorado
COL	Collisions
CRM	Crew Resource Management
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CT	Connecticut
CY	Calendar Year
DAFIF	Digital Aeronautical Flight Information File
DH	Decision Height
DQI	Data Quality Index
DSNA	Direction des Services de la Navigation Aerienne
d-TPP	Digital – Terminal Procedure Publication
DV	Dependent Variable

EAD	European AIS Database
EASA	European Aviation Safety Agency
easyJet	easyJet plc
EBITDA	Earnings before Interest, Taxes, Depreciation, and Amortization
ECAST	European Commercial Aviation Safety Team
ECCAIRS	European Coordination Centre for Accident and Incident Reporting Systems
EMAS	Engineered Materials Arresting Systems
ESARR	EUROCONTROL Safety Regulatory Requirement
ESD	Event Sequence Diagram
ETMSC	Enhanced Traffic Management System Counts
EU	European Union
EURBASE	European Military Bird Strike Database
EUROCONTROL	European Organisation for the Safety of Air Navigation
EX	Excursions
FAA	Federal Aviation Administration
FAROS	Final Approach Runway Occupancy Signal
FDM	Flight Data Monitoring
FDP	Flight Data Processor
FFB	Fact Finding Board
FMGS	Flight Management and Guidance System
FMS	Flight Management System
FO	Foreign Object
FOD	Foreign Object Damage
FSF	Flight Safety Foundation
FT	Fault Tree
FY	Fiscal Year
GA	General Aviation
GAIN	Global Aviation Information Network
GAO	Government Accountability Office
GC	Ground Control
GIS	Geographic Information System
GPU	Ground Power Unit

HEIDI	Harmonisation of European Incident Definitions Initiative
HI	Hawaii
HTA	Hierarchical Task Analysis
IATA	International Air Traffic Association
IBIS	ICAO Bird Strike Information System
ICAO	International Civil Aviation Organization
ID	Idaho
IFALPA	International Federation of Airline Pilots' Associations
IFR	Instrument Flight Rules
IFS	Industrial and Financial Systems
IL	Illinois
ILS	Instrument Landing System
ILS CAT I	Instrument Landing System Category I
ILS CAT II	Instrument Landing System Category II
ILS CAT III	Instrument Landing System Category III
IMC	Instrument Meteorological Conditions
IN	Incursions
IN	Indiana
IRP	Integrated Risk Picture
IT	Information Technology
IV	Independent Variable
KPA	Key Performance Area
KPI	Key Performance Indicator
LA	Los Angeles
LA	Louisiana
LAWA	Los Angeles World Airports
LAX	Los Angeles International Airport
LC	Local Control
LEI	Lack of Effective Implementation
LOSA	Line Operations Safety Audit
LPL	Liverpool John Lennon Airport
MA	Massachusetts
MAFF	Central Science Laboratory of the Ministry of Agriculture,

	Fisheries and Food
Max	Maximum
MCDA	Multi-Criteria Decision Analysis
ME	Maine
MESYS	MessageSystem
METAR	French Meteorologique Aviation Regulier
MI	Michigan
Min	Minimum
MLE	Maximum Likelihood Estimation
MLS	Microwave Landing System
MN	Minnesota
MORS	Mandatory Occurrence Reporting Scheme
MT	Montana
MUAC	Maastricht Upper Area Control Centre
N	Sample Size
NAIMS	National Aviation Incident Management System
NAS	National Aerospace Standards
NASA	National Aeronautics and Space Administration
NATCA	National Air Traffic Controllers Association
NAVAID	Navigational Aid
NC	Norwegian Customs
ND	North Dakota
NDB	Non-Directional Beacon
NE	Northeast
NextGen	Next Generation Air Transport System
NFDC	National Flight Data Centre
NH	New Hampshire
NJ	New Jersey
NLR	National Aerospace Laboratory of the Netherlands
NM	New Mexico
NMACS	Near Midair Collision System
NMR	Northwest Mountain Region
NO	Norway

Norwegian	Norwegian Air Shuttle ASA
NOTAM	Notice to Airman
NPA	Notice of Proposed Amendment
NPRM	Notice of Proposed Rulemaking
NPTRS	National Program Tracking and Reporting Subsystem
NTSB	National Transportation Safety Board
NTSC	National Transportation Safety Committee of Indonesia
NV	Nevada
NY	New York
NZ	New Zealand
OASIS	Occurrence Analysis and Safety Investigation System
OD	Operational Deviation
OE	Operational Error
OEM	Original Equipment Manufacturer
OEDS	Operational Error / Deviation System
OH	Ohio
OK	Oklahoma
OSL	Oslo Lufthavn AS
OR	Oregon
PA	Pennsylvania
PAPI	Precision Approach Path Indicator
PD	Pilot Deviation
PDS	Pilot Deviation System
Peel	Peel Airports Limited
PM	Process Model
PO	Private Organisation
PR	Public Relations
RAT	Risk Analysis Tool
RI	Rhode Island
RI	Runway Incursion
RNoAF	Royal Norwegian Air Force
ROW	Runway Overrun Warning
ROP	Runway Overrun Prevention

RPK	Revenue Passenger Kilometres
RPM	Revenue Passenger Miles
RSAT	Runway Safety Action Team
RVR	Runway Visual Range
RWSL	Runway Status Lights
RWY	Runway
SAFREP	Safety Data Reporting and Data Flow
SARP's	Standards and Recommended Practices
SD	Standard Deviation
SD	South Dakota
Sentinel	Sentinel Safety Information Management System
SESAR	Single European Sky ATM Research
SHEBBA	Safety, Health, Environment, BAA
SHELL	Software, Hardware, Environment, Liveware
SID	Standard Instrument Departure
Signature	Signature Flight Support
SME	Subject Matter Expert
SMM	Safety Management Manual
SMS	Safety Management System
SMSM	Safety Management System Manual
SSP	State Safety Program
STAR	Standard Arrival Route
SW	Southwest
TAIC	New Zealand Transport Accident Investigation Commission
TIPH	Taxi Into Position and Hold
TMA	Terminal Manoeuvring Area
TRACON	Terminal Radar Approach CONtrol
TRB	Transportation Research Board
TSA	Transportation Security Administration
TSB	Transportation Safety Board of Canada
TWR	Aerodrome Control Tower
TWY	Taxiway
TX	Texas

UK	United Kingdom
UK CAA	UK Civil Aviation Authority
ULD	Unit Load Device
UML	Unified Modelling Language
UN	United Nations
U.S.	United States
USDA	United States Department of Agriculture
USOAP	Universal Safety Oversight Audit Programme
UT	Utah
WA	Washington
WAAS	World Aircraft Accident Summary
WI	Wisconsin
Wideroe	Wideroe Flyveselskap
WLU	Work Load Unit
WOC	Washington Operations Centre
WP	Western-Pacific
WS	Wildlife Strikes
WSM	Weighted Sum Method
WY	Wyoming
V1	Decision Speed
VASI	Visual Approach Slope Indicator
VFR	Visual Flight Rules
VGSI	Visual Glide Slope Indicator
VHF	Very High Frequency
VIP	Very Important Person
VMC	Visual Meteorological Conditions
VOLPE	John A. Volpe National Transportation Systems Center
VOR	VHF Omnidirectional Range
V/PD	Vehicle Driver / Pedestrian
V_R	Rotation Speed
VT	Vermont

1 Introduction

This chapter presents the context of the research in this thesis by examining the role of safety management in preventing accidents and other incidents on the airport surface (i.e. runways and taxiways). It establishes the rationale for the need for a holistic and comprehensive framework for the assessment of airport surface safety and formulates seven research objectives for its realisation. This is followed by a brief description of the structure of the thesis.

1.1 Background

The demand for air travel has increased steadily over the years such that air transport is now a major contributor to global economic prosperity. Since the mid-1980s, passenger numbers have more than doubled, while freight traffic has increased almost three-fold (Air Transport Action Group, 2005, 2012). Despite the recent economic recession, this trend is expected to continue over the next 20 years. Indeed, forecasts suggest that world passenger traffic (by revenue passenger-kilometres) and air cargo (by revenue tonne-kilometres) will grow annually by 5.0 and 5.2%, respectively (Boeing Commercial Airplanes, 2012a).

Airports are a vital component of the air transport system. Although they can be quite different from each other, e.g. some may have a single runway whilst others have six, they have the same basic function, which is the provision of a safe and efficient transition of passengers and goods between the ground and airspace. Whilst airports have considerable infrastructure, the most apparent being the terminals, it is actually operations on the airport surface that are crucial to achieving this function.

The airport surface, which is the runway and taxiway system, accommodates the ground movement of aircraft. By its very nature, surface operations require the input of various actors. Aircraft use the airport surface for landing, taxiing and take-off. Arriving flights land on a runway and then use the surface to taxi to their assigned ramp at the apron, where ground handling (servicing) takes place. Conversely, departing flights use the taxiway system to taxi from their ramp at the apron to an assigned runway for take-off. Vehicle drivers and pedestrians (V/PD), e.g. those associated with the airport authority and responsible for the management and maintenance of the airport surface, also use the runway and taxiway system. To ensure a safe flow of aircraft on this surface is the role of Air Traffic Control (ATC). Finally, it is the duty of the regulatory bodies to oversee the system by specifying the rules and regulations governing the different aviation stakeholders and ensuring their compliance.

Given the number of actors and their interactions, it is easy to see just how complex surface operations are. Unsurprisingly, this increases the level of vulnerability on the airport surface, presenting an appreciable level of risk of failure with the consequent potential for the occurrence of accidents and incidents. Research by the Flight Safety Foundation (2009) revealed that from 1995 to 2008, a total of 1,429 commercial transport aircraft were involved in aviation accidents. Of these, approximately 30.0% were runway related, leading to 973 fatalities. This highlights the potentially catastrophic nature of accidents on the airport surface. In addition to accidents, incidents in which safety is compromised also occur on the airport surface. For example, there were 951 runway incursions, in 2009 in the United States (U.S.) (Federal Aviation Administration, 2010d). Furthermore, it is not just runways that are of concern as accidents and incidents can equally occur on taxiways. Therefore, effective risk mitigation strategies must incorporate both the runways and taxiways at an airport. In fact, airport surface safety has been acknowledged to be a key area of aviation safety by aviation stakeholders worldwide (International Civil Aviation Organization, 2010; National Transportation Safety Board, 2012) and, therefore, this thesis addresses the safety of surface operations.

To avoid situations that compromise safety and lead to accidents and incidents, airports are supposed to implement a Safety Management System (SMS). The SMS provides a systematic approach to managing safety and has four components: safety policy and objectives, safety risk management, safety assurance, and safety promotion. At the core of the SMS is operational safety management (risk management), which supports the development of evidence-based measures for the overall safety management process, such

as key performance indicators of safety. In practice, safety risk management is concerned with safety data – its reporting, collection, investigation and analysis – and the subsequent development of measures for the mitigation of the safety risks. To do this properly, it is essential that safety risk management addresses the entire architecture of a system (International Civil Aviation Organization, 2009e).

Although an international legislative framework for airport SMS exists, national regulations are still under development. Therefore, little practical guidance for its deployment and implementation is currently available. Yet to date, initiatives for the management of surface safety have addressed the issue from various single viewpoints including, regulatory bodies at the national and international levels (the International Civil Aviation Organization, 2007), multinational aviation safety organisations (Flight Safety Foundation, 2009), Air Navigation Service Providers (ANSPs) (Federal Aviation Administration, 2010d), and aircraft manufacturers (Airbus, 2009). In addition, there have been action plans at the local airport level (e.g. training campaigns). These initiatives highlight not only the divided attention surface safety receives but also the biggest limitation in the safety management of surface operations: i.e. single accident or incident type focus of current initiatives associated with the viewpoint of a specific aviation stakeholder.

The current approaches to the analysis of accidents and incidents on the airport surface are piecemeal focus on the mitigation and prevention of specific occurrence types, and often for particular scenarios (e.g. runway-related occurrences only). The consequence of this is that awareness for surface safety is channelled towards specific scenarios, discarding that others have the potential to result in a fatal accident.

Typical examples for surface safety analysis and mitigation efforts include the European Organisation for the Safety of Air Navigation's (EUROCONTROL) Integrated Risk Picture (IRP) and the Causal Model for Air Transport Safety (CATS) developed by the Nationaal Lucht- en Ruimtevaartlaboratorium (NLR). Both models have developed detailed mathematical models of specific accidents and incidents of relevance to the airport surface, e.g. the IRP includes runway and taxiway collisions, whilst CATS considers runway excursions and incursions. Yet despite this, both models suffer from the drawback of the focus on a particular stakeholder perspective, with the IRP focussed on ATC and CATS concerned with the flight perspective. Therefore, a large amount of information relevant to surface operations is not considered in each model and hence they are of limited relevance in risk mitigation to stakeholders other than those for which they were created

(Ale*, et al.*, 2009; The European Organisation for the Safety of Air Navigation Experimental Centre, 2006).

Whilst such a piecemeal approach might be acceptable at an organisational level as stakeholders are interested in determining the risk related to their operations, however, it is also found at the highest level of legislation. For instance, the International Civil Aviation Organisation's (ICAO) 'Manual on the Prevention of Runway Incursions' (International Civil Aviation Organization, 2007), provides recommendations for the mitigation of runway incursions at a global level. However, its development is based on subject matter expert (SME) opinion and fails to capture various factors that are critical in the context of runway incursions. For example, the manual does not account for factors related to vehicle and pedestrian operations (e.g. vehicle technical failures, V/PD competences) on the airport surface.

Previous analyses also show methodological limitations. These include: missing or ambiguous definitions, insufficient specification of safety data, data quality concerns (e.g. data accuracy), and unspecified analysis methodologies. The Flight Safety Foundation (2009), for instance, initiated a major study to analyse risk factors in runway excursions and recommended safety risk enhancements based upon the results of the analysis. However, this study fails to account for all types of excursions, uses aggregate accident data without assessing its quality and does not specify how the risk factors are extracted from the data.

In summary, the current non-integrated approach to safety management has developed from the consideration of specific stakeholder interests. It neglects the operations of the other relevant stakeholders, and their inter-dependencies, with the consequent impact of less than effective mitigation measures. Therefore, a holistic (integrated) safety assessment of airport surface operations is required, based on a reliable methodology and following the requirements (specified by the ICAO) of safety management systems. Such an approach will enable truly effective risk mitigation strategies to be developed for the airport surface. This thesis develops such a holistic model of airport surface safety.

1.2 Aim and Objectives

From the background above, the aim of this thesis is to develop a framework for a holistic airport surface safety management. The framework proposes a systematic approach to safety management by modelling the airport architecture and the process of surface operations, determining its failure modes and their underlying causal factors, developing a macroscopic scenario tool to evaluate changes in the system architecture and proposing a functional relationship model to quantify the system in terms of safety. Safety data and other data sources feed the framework and a dedicated data pre-processing strategy ensures its validity. Based upon this, recommendations for safety enhancement strategies are proposed. Seven research objectives have been formulated to achieve this aim. These are to:

1. Model the physical and functional architecture of airports and define its variability.

Developing a descriptive model of the airport architecture allows understanding the higher-level structures and the context of airport safety management. Defining the variability of the airport system architecture will later help to specify the research requirements.

2. Develop a 4-dimensional process model of airport surface operations.

The operations on the airport surface (runways and taxiways) are crucial to the achievement of the airport's functionality. Following the definition of the static airport architecture, the second objective addresses the dynamics of its operations and aims to develop a process model of surface operations. Such a model helps understanding the tasks of the stakeholders and their interaction with physical airport surface infrastructure as well as the overall airport surface system architecture.

3. Provide a systematic literature review to highlight the limitations of current approaches and potential barriers to the effective mitigation of airport surface accidents / incidents.

The review has the goal to set the initial research requirements. The incorporation of further specifications derived from the variability of airports and the characteristics of surface operations aids the development of a robust framework for an integrated analysis of airport surface safety.

4. Develop a data validation framework.

Based on the research requirements a strategy for the collection of a reference data set is derived. To ensure the validity of the data, a framework for data quality assessments that accounts for the specific characteristics of airport surface safety data is developed.

5. Determine the causal factors underlying airport surface accidents / incidents.

The aim is to get a holistic understanding of the causes to accidents / incidents, to identify the contribution of the individual actors and to summarise the results in a new taxonomy.

6. Develop a macroscopic scenario tool to support the safety management of airport surface operations.

The research objective aims at developing a model that shows how each component of the airport surface system architecture can fail. As the airport environment is dynamic and, therefore, characterised by change, such a model can also provide a macroscopic scenario tool to evaluate the impact of changes in the airport surface system and to guide further analysis.

7. Propose a systematic framework to assess the functional relationship between airport surface accidents / incidents and their underlying causal factors.

The last research objective aims at proposing a methodology for the quantification of the airport surface system in terms of safety and to provide recommendations for safety enhancement strategies.

1.3 Thesis outline

Chapter 2 discusses the context for airport safety management and the need for research. It defines the airport system, both in architectural and functional terms, and highlights the central role of airport surface operations and the need for an appropriate safety management system. The current management of the airport surface is discussed in Chapter 3 and used to develop an initial process model of normal airport surface operations. This model describes the physical airport surface infrastructure together with

the tasks and interactions of the relevant stakeholders, and serves as a baseline model for the subsequent development of the SMS in this thesis.

Chapter 4 addresses the fundamentals of safety and SMS and defines the requirements for SMS. In addition, the current status of its implementation in airports is identified. Subsequently, Chapter 5 systematically reviews the state-of-the-art of airport surface safety analysis and mitigation strategies. The aim is to emphasise the current approaches in relation to the SMS requirements established in Chapter 4. Based on the system architecture, the requirements of SMS and the limitations of previous research, a framework for an integrated analysis of airport surface safety is proposed.

In order to analyse the safety of surface operations using the proposed framework a reference data set combining twelve databases from airlines, airport operators, ANSPs, ground handling companies and regulators is collected in Chapter 6. To assess the quality of this dataset a data quality assessment framework is developed that accounts for the specific characteristics of airport surface safety data. In particular, the data is assessed for its internal validity, external validity and in terms of reporting levels, and each database is rated using a Data Quality Index (DQI). In addition, recommendations are offered for reporting systems and safety policies.

Chapter 7 and 8 present the analysis of the data (captured in Chapter 6) to determine causal factors using a hybrid methodology. The methodology is applied at the State-level in Chapter 7 and at the cross-State level in Chapter 8. Subsequently, the results are used to specify a new taxonomy (Chapter 9). This taxonomy provides a common industry language and state-of-the-art tool to support the data analysis function in the context of SMS. Its unique features are its integration and applicability to all relevant aviation stakeholders. In addition, a cross-stakeholder comparison serves to give a unique insight into the contribution of each of the stakeholders and to explain the differences in causal factors and their drivers.

After the airport surface operations have been modelled and the drivers to safety identified, the results are combined in Chapter 9 to develop a macroscopic scenario tool, which supports the management of change (i.e. safety assurance), training and education, as well as the safety communication functions of SMS (i.e. safety promotion).

Chapter 10 analyses the impact of the airport and its characteristics on the occurrence of airport surface safety accidents / incidents. The relevant data is collected through an airports survey. Using this data, Chapter 11 develops a systematic analysis framework to model the functional relationship between occurrences and their underlying causal factors.

Following this framework, the airport surface system architecture is dissected into its elements with each component and their interactions analysed separately. This provides a more detailed analysis compared to traditional accident / incident analysis methods. In addition, Chapter 11 summarises this research by presenting the overall framework for a holistic airport safety management.

The thesis ends with Chapter 12 with a summary of the contributions of this thesis. Furthermore, recommendations for future research and a list of publications from the research presented in this thesis are given. Figure 1 captures the high level structure of this thesis.

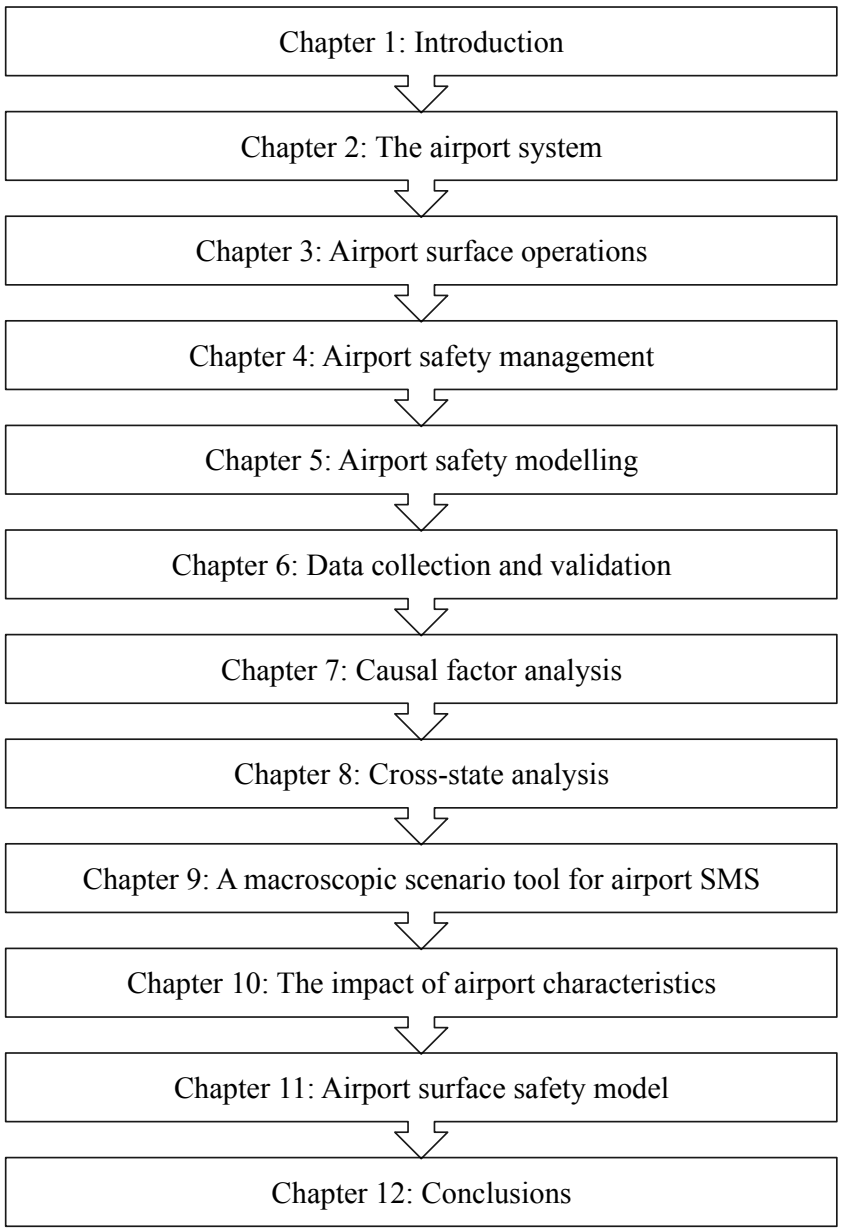


Figure 1: Overview of thesis structure

2 The Airport System

A prerequisite for the development of a holistic framework to assess airport surface safety is to define the airport environment. Therefore, and to address the first research objective, this chapter develops a model of the airport architecture, which is applied in three case studies to identify the physical and functional variability in airports. This is achieved in six parts.

To begin with, the airport architecture in terms of its physical infrastructure, operations, and key actors is defined. Subsequently three case studies are used to identify the variability in the system architecture. The third part introduces the critical role of surface operations for the airport's functionality and part four introduces the Key Performance Indicators (KPI's) used to measure airport performance and discusses their drivers. Subsequently, the importance of safety is highlighted and current approaches to addressing surface safety are introduced, before part six concludes this chapter.

2.1 Airports and their Function in the Air Transport System

The International Civil Aviation Organization (ICAO) defines an *aerodrome* as "a defined area on land or water (including any buildings, installations and equipment) intended to be used either wholly or in part for the arrival, departure and surface movement of aircraft" (International Civil Aviation Organization, 2004b). Although, often used interchangeably in the aviation industry, the terms *airport* and *aerodrome* are different, as the former refers to aerodromes for which a certificate has been issued by the appropriate authorities (Transport Canada, 2010a). States are required to certify aerodromes used for

international operations in accordance with the specifications contained in Annex 14 to the Chicago Convention as well as other relevant ICAO specifications through an appropriate regulatory framework (International Civil Aviation Organization, 2004b).

2.2 System Architecture

In order to understand the airport function, it is necessary to define the airport system architecture in terms of its components, operations and the key actors or stakeholders.

2.2.1 Airport Components

Airports consist of two major components: landside and airside (Ashford*, et al.*, 1997; deNeufville and Odoni, 2003; Horonjeff and McKelvey, 1994; Janic, 2000; Wells, 1996).

The landside comprises the ground-access system (e.g. road network and public transportation facilities), the terminals, and the interface between the ground-access system and the terminal buildings (i.e. curbside). The terminal area is split into a publicly accessible side and a restricted access area. Whilst the passenger processing areas (e.g. the ticketing, check-in and arrivals greeting areas) are accessible to the public, access to the departure and arrival concourses, and the baggage reclaim area is restricted to passengers holding a valid boarding pass and airport personnel. Depending on the underlying system, however, national differences may be encountered. For instance, the baggage reclaim area is within the restricted access zone at European airports, whilst in the U.S. these facilities are accessible to the public. Finally, the control tower is located on the landside.

The airside facilities are those where the aircraft operations and supplementary services are carried out and access from landside to airside is subject to strict controls. The airside facilities include the gates that connect the terminal to the aircraft, the apron / ramp, which are used for ground handling activities (e.g. loading and fuelling), and the runway (RWY) and taxiway (TWY) system (airport surface or manoeuvring area), and associated infrastructure (e.g. lighting, markings and signage). In addition, cargo and mail processing, fire fighting, hangars, and other facilities (e.g. for general aviation – GA) may be located on the airside.

2.2.2 Airport Operations

Airports are involved in various operations (activities). The term operation refers to "an organised activity involving a number of people" (Oxford Dictionaries, 2013). When mapping these activities to the components section 2.2.1, they can be summarised into six management categories: access facilities, terminal and passenger, apron, manoeuvring area, airside (activities simultaneously applicable to apron, airport surface and outer surface areas), and general. From the literature (Ashford*, et al.*, 1997; deNeufville and Odoni, 2003; Horonjeff and McKelvey, 1994; International Civil Aviation Organization, 2009e; Janic, 2000; Kazda and Caves, 2000; Wells, 1996) the six management categories can be further broken down as follows:

1. Access facilities management
    - Parking
    - Shuttle services
    - Other transport services (e.g. taxies, limousines and car rental)
2. Terminal and passenger management
    - Service (e.g. public information)
    - Check-in
    - Security
    - Sales and retail
    - Customs
    - Immigration
    - Baggage flow management and facilities (e.g. baggage claim, left luggage and trolley management)
    - Very Important Person (VIP) assistance
    - Mail and cargo processing
3. Apron management
    - Gate / stand allocation
    - Gate operations
    - Flight dispatch and ground handling
    - Rules and regulations for airside operations
    - Vehicle management (e.g. licensing)
    - Push-back and towing operations

- Taxi operations
- Apron inspection and management

4. Manoeuvring area management
   - Manoeuvring area inspection and maintenance (e.g. winter operations)
   - Construction management
   - Taxi and departure / arrival operations
5. Airside management
   - Air traffic and aeronautical information and communications services
   - Radio navigation aids installations and maintenance
   - Wildlife hazard management
   - Obstacle control
   - Follow-me guidance and marshalling
   - Disabled aircraft removal
6. General airport management
   - Aerodrome emergency planning (e.g. emergency procedures and simulation practices)
   - Rescue and fire fighting (e.g. equipment, facilities maintenance and training)
   - Safety and security
     - Implementation of a Safety Management System (SMS)
     - Implementation and monitoring of a security programme
     - Implementation and monitoring of an aerodrome emergency plan
     - Processing of the applications for the issuance of access cards
   - Slot negotiation and allocation
   - Cleaning and waste removal
   - Coordination with multi-agencies / dealing with stakeholders (e.g. local communities)
   - Public information (external).

Figure 2 summarises the physical and functional airport architecture. The arrows represent the flow of passengers through the airport system.

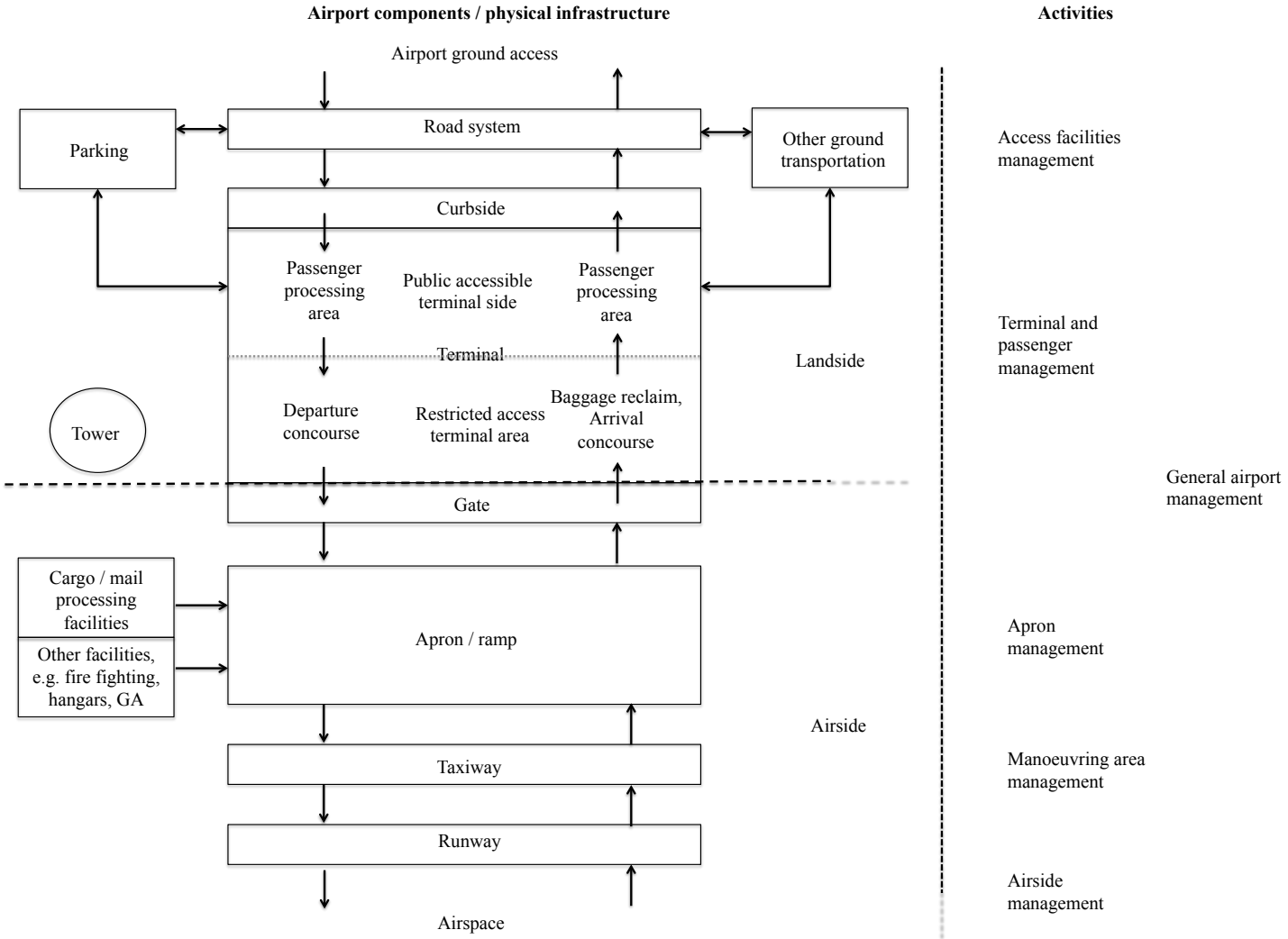


Figure adapted from Ashford, *et al.* (1997), deNeufville and Odoni (2003), Horonjeff and McKelvey (1994), Janic (2000), Kazda and Caves (2000), Wells (1996)

Figure 2: Physical and functional architecture of airports

2.2.3 Key Actors or Stakeholders

Various actors or stakeholders are involved in airport operations. The principle actors directly responsible for safe and efficient airport operations are the airport authority, airlines, ground handling companies, Air Navigation Service Providers (ANSPs), and various contractors. In addition, external stakeholders, such as local communities or the government, interact with the airport. All operations are carried out in accordance with the relevant regulations.

2.2.3.1 Airport Operator

The airport is owned and operated by the airport authority (airport operator), which may be a governmental or a non-governmental (privatized) entity. Its responsibilities include the management and oversight operations. Although the airport authority can be directly responsible for the activities in section 2.2.2, many are delivered through lease agreements and sub-contracts. Where this is the case, the airport authority is responsible for the management of the sub-contractors and tenants. For example, air traffic control services are often provided by an independent ANSP, or shops in the sales area are usually leased to commercial entities. Typical activities that are run by the airport authority itself include, construction, facilities and infrastructure management, maintenance, and general airport management (Wilding, 2007).

2.2.3.2 Airlines

Airlines are service providers, whose basic function is the transportation of people and goods. They use aircraft, which provide the physical infrastructure that enables transportation in the air. Airlines operate a network that connects different locations (i.e. airports). The core of an airline's operations includes flight operations (i.e. the management of flights, including, flight planning, training and crew scheduling), ground operations (e.g. traffic handling and ramp handling), and maintenance and engineering. These operations are supported by other more administrative functions (e.g. finance and sales). Similar to the airport authority, airlines can also sub-contract some of their

activities. For instance, ground handling is often sub-contracted to specialised service providers as outlined in the next section (International Air Traffic Association, 2013).

These days, airlines are often part of an alliance, which is a cooperation agreement between two or more airlines. A key feature of alliances is code sharing, i.e. agreements whereby airlines share the same flight. That means passengers can book a seat on one airline, though the flight is actually operated by another one. This allows airlines both to offer a wider network without having to schedule extra flights, and to provide a more seamless travel experience for passengers through that network (Goh and Uncles, 2003). For example, Star Alliance's 27 member airlines together serve a network of 1,356 airports in 193 countries (Star Alliance, 2013).

2.2.3.3 Ground Handling Companies

Ground handling services comprise the two functions of traffic and ramp handling. The former are mainly landside services at passenger and / or cargo terminals. The main services include passenger handling (e.g. ticketing, check-in and executive lounges), cargo and mail handling, and information services. Ramp handling refers to operations in relation to the servicing of aircraft which take place on the airside. Typical services include aircraft loading and unloading, baggage handling, fuelling and de-icing. Several different companies can provide handling services for one flight. In fact, at least two suppliers (one of which has to be independent of the airport or the dominant airline) for each category of ground handling services (e.g. baggage handling, ramp handling, fuel and oil handling) must offer services at larger European airports to ensure that airports remain competitive (European Commission, 2012).

The airport authority, airline, or an independent operator, i.e. ground handling company, can offer these services but the market share of these stakeholders varies greatly across different regions of the world. While many European airport operators offer handling services, those in the U.S. do not. Indeed, in North America ground handling is most commonly performed by airlines themselves, either through self-handling or third-party handling (e.g. another airline). However, this practice (ground handling by airlines), is prohibited at many airports elsewhere. Independent ground handling companies must have a concession to operate at an airport and undergo regular audits from both airports and airlines (deNeufville and Odoni, 2003).

2.2.3.4 Air Navigation Service Providers

Air Navigation Service Providers (ANSPs) provide Air Traffic Control (ATC) and navigation services for the aircraft that fly in controlled airspace. Aircraft typically use airways, assigned routes in the air similar to a road system in the sky, to fly from one airport to another. It is ATC's task to control the aircraft along these airways and to make sure that the required separation is maintained.

At the airport, ground control and the aerodrome control tower (TWR) coordinate the ground movements and direct pilots onto the runway and into the air. Once the aircraft is airborne, the Approach Control unit (AAP) provides separation for the climb and descent phase of flight. En-route, ATC services are provided by the Area Control Centre (ACC) (NATS, 2013; Subotic, 2007).

2.2.3.5 Contractors

As previously noted, various airport services (e.g. sales, restaurants, cleaning and general security) are provided by contractors. The contractors must follow the rules and procedures set by the regulator (e.g. security regulations) and local airport operator (e.g. safety measures such as airside vehicle driver training).

2.2.3.6 Regulators

ICAO requires each member state "to provide for the safe and efficient operation of aircraft within its airspace" (International Civil Aviation Organization, 2006e). Each State signatory to the Chicago Convention is obligated to provide infrastructure and services, including adequate airports, navigation aids, charting and instrument approach minima, weather reporting, air traffic services, search and rescue, aviation security, and the timely correction of safety deficiencies. A Civil Aviation Authority (CAA) executes the proactive supervision and regulation of aviation activities. Under the convention and its annexes, it is the State's responsibility to provide, and hence the CAA's responsibility to execute:

- Licensing of operational personnel;
- Certification of aircraft, air operators and aerodromes;

- Control and supervision of licensed personnel, certified products and approved organisations;
- Provision of air navigation services (including meteorological services, aeronautical telecommunication, search and rescue services, charts, and the distribution of information); and
- Aircraft accident and incident investigation.

Therefore, in each state, a CAA has to develop and implement acceptable certification, licensing and operating processes to ensure safe and efficient airport operations. Furthermore, it has to oversee that all stakeholders comply with the established regulations.

2.2.3.7 External Stakeholders

An airport is not a self-contained entity; rather, it actively interacts with external stakeholders. Airports, then, are part of a wider air transport system that also includes aircraft / airlines, Air Traffic Management (ATM) and customers / system users. This air transport system is embedded in the natural environment and regulated by national and international authorities (Subotic, 2007) as illustrated in Figure 3.

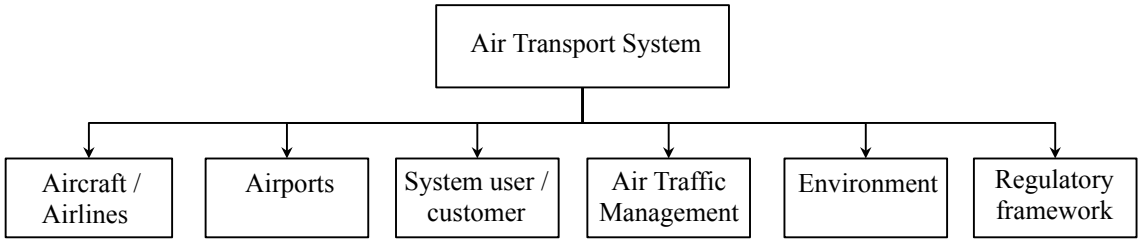


Figure adapted from Subotic (2007)

Figure 3: Air transport system

As introduced in section 2.2.3.2, the airlines' role in this system is to transport people and goods by means of aircraft. Therefore, the users of the system are either passengers and individuals, or organisations that transport goods around the world. The interface between airlines and its users is the airport. Another major component of this system is Air Traffic Management (ATM), whose major objective is "to enable aircraft operators to meet their planned times of departure and arrival and adhere to their preferred flight profiles with minimum constraints, without compromising agreed levels of safety" (The European

Organisation for the Safety of Air Navigation, 2005). ATM is composed of a number of complementary systems namely; airspace management, Air Traffic Flow and Capacity Management (ATFCM) and Air Traffic Control (ATC) (The European Organisation for the Safety of Air Navigation, 2011e).

Regulatory bodies oversee this system by providing a framework of rules and regulations and ensuring the compliance of the different aviation stakeholders. While regulatory bodies exist at a national level, multinational organisations have been created to oversee and harmonise regulatory requirements. The ICAO, an agency of the United Nations (UN), founded in 1944, sets regulations and standards at an international level that have to be adopted by its 190 member states (International Civil Aviation Organization, 2011d). According to Article 44 of the Chicago Convention, the agency is required to "insure the safe and orderly growth of international civil aviation throughout the world" (International Civil Aviation Organization, 2006d). This is achieved through the promulgation of Standards and Recommended Practices (SARP's), published in the Annexes to the Chicago Convention (International Civil Aviation Organization, 2011b).

The European Aviation Safety Agency (EASA) is the European regulatory body and was established in 2002 to ensure a high and uniform level of safety throughout the European Union (EU) by means of the implementation of common safety rules and measures. Its responsibilities include certification and the development and implementation of safety rules (The European Organisation for the Safety of Air Navigation SKYbrary, 2011). In addition, multinational cooperative bodies have been established. The European Organisation for the Safety of Air Navigation (EUROCONTROL) is committed to the development of a Single European Sky: a seamless, pan-European ATM system. Its activities include, for example, research on the pan-European ATM network, support for rule making and regulations in European aviation, as well as network management (The European Organisation for the Safety of Air Navigation, 2010a).

Besides the stakeholders within the air transport system, other external stakeholders, such as government, local communities, investors and suppliers have political, economic, and social interests in airports (Luchtverkeersleiding Nederland, 2007).

2.2.4 Airport Heterogeneity

While the literature has identified that airports are homogeneous in their main characteristics (i.e. components, activities and key actors), it has also shown that, at a lower level, these features may vary (e.g. various stakeholders can be responsible for the activities introduced in section 2.2.2). To analyse how airports differ in their characteristics and to augment the literature, three case studies are presented here.

The objective of these case studies is to analyse three airports in terms of their components, stakeholder responsibility for activities and key actors. By such an analysis, the variant and invariant characteristics of the airport architecture can be derived and the functionality of airports assessed. To capture the various features of airports, including different underlying operations and regulations, the criteria for the selection of appropriate airports were set as follows:

- Airports from different countries in Europe and North America that are subject to varying regulations,
- Airports with different types of ownership, and;
- Airports of different size in terms of the number of aircraft movements and passenger boarding.

According to these criteria, Los Angeles International Airport (LAX) in the U.S., Liverpool John Lennon Airport (LPL) in the United Kingdom (UK), and Bodo Airport (BOO) in Norway (NO) were chosen. The case studies included airfield tours given by senior operational personnel and structured communications with them. The aim was to identify to what extent each airport conforms to airport architecture derived from the literature outlined in the previous sections. Thus, it was important to seek the opinions and views of personnel in senior positions (e.g. supervisors) with a minimum of 15 years of experience in aviation, airport operations and their safety. As of November 2005, airports are required through Annex 14 to the Convention on International Civil Aviation (ICAO, 2004b) to have a SMS in operation. However, safety-critical thinking emerged in the aviation industry during the 1990s (Stolzer*, et al.*, 2011) and, therefore, a minimum of 15 years of aviation experience ensures that the relevant personnel are both knowledgeable about the operations and have the necessary awareness for their safety.

The structured communications were, therefore, conducted with:

- An Airfield Operations Superintendent at LAX,

- The Head of Health, Safety and Regulatory Compliance at LPL, and
- The ATC Tower Supervisor at BOO.

The tours covered both landside and airside facilities. This included the terminals, the aprons (both commercial and GA facilities), the manoeuvring area and the perimeter roads. The baseline model of airport components introduced in Figure 2 was the basis of the guided tours and the personnel were asked to identify each of the components successively from the landside to airside. Communication with the operational personnel facilitated the identification of each component and the tours enabled the development of a spatial image of the airports. The guided tours also facilitated the understanding of airport operations which will be detailed in Chapter 3.

In addition, the list of airport operations compiled in section 2.2.2 and the key actors (section 2.2.3) were discussed with the operational personnel in order to identify the operations applicable to each airport and the corresponding stakeholders. Table 1 presents the operational characteristics of the three chosen airports.

Table 1: General airport characteristics

Characteristic	**LAX**	**LPL**	**BOO**
Location	United States	United Kingdom	Norway
Passenger boarding (2011)	61, 862,52	5,251,161	1,556,924
Aircraft movements (2011)	603,912	69,055	43,520
Airport operator	Los Angeles World Airports (LAWA)	Peel Airports Limited (Peel)	Avinor & Royal Norwegian Air Force (RNoAF)
Ownership	City of Los Angeles	Private organisation	State-owned organisation & Military

Sources: Avinor AS (2012a); Los Angeles World Airports (2012); UK Civil Aviation Authority (2012)

LAX is a major hub airport in North America and is one of the busiest airports in the world. According to Airports Council International (ACI) it was ranked third in terms of aircraft movements, and sixth in terms of passenger boarding in 2010 (Airports Council International, 2012a). LPL is a medium-sized airport in the UK with mainly domestic traffic and a few international connections. BOO is a regional airport in Norway with a unique feature of shared civilian and military facilities.

Figures 4 to 6 show the components of the three airports. The differences compared to the baseline model introduced in section 2.2.1, Figure 2, are highlighted in red and the individual characteristics shown in blue.

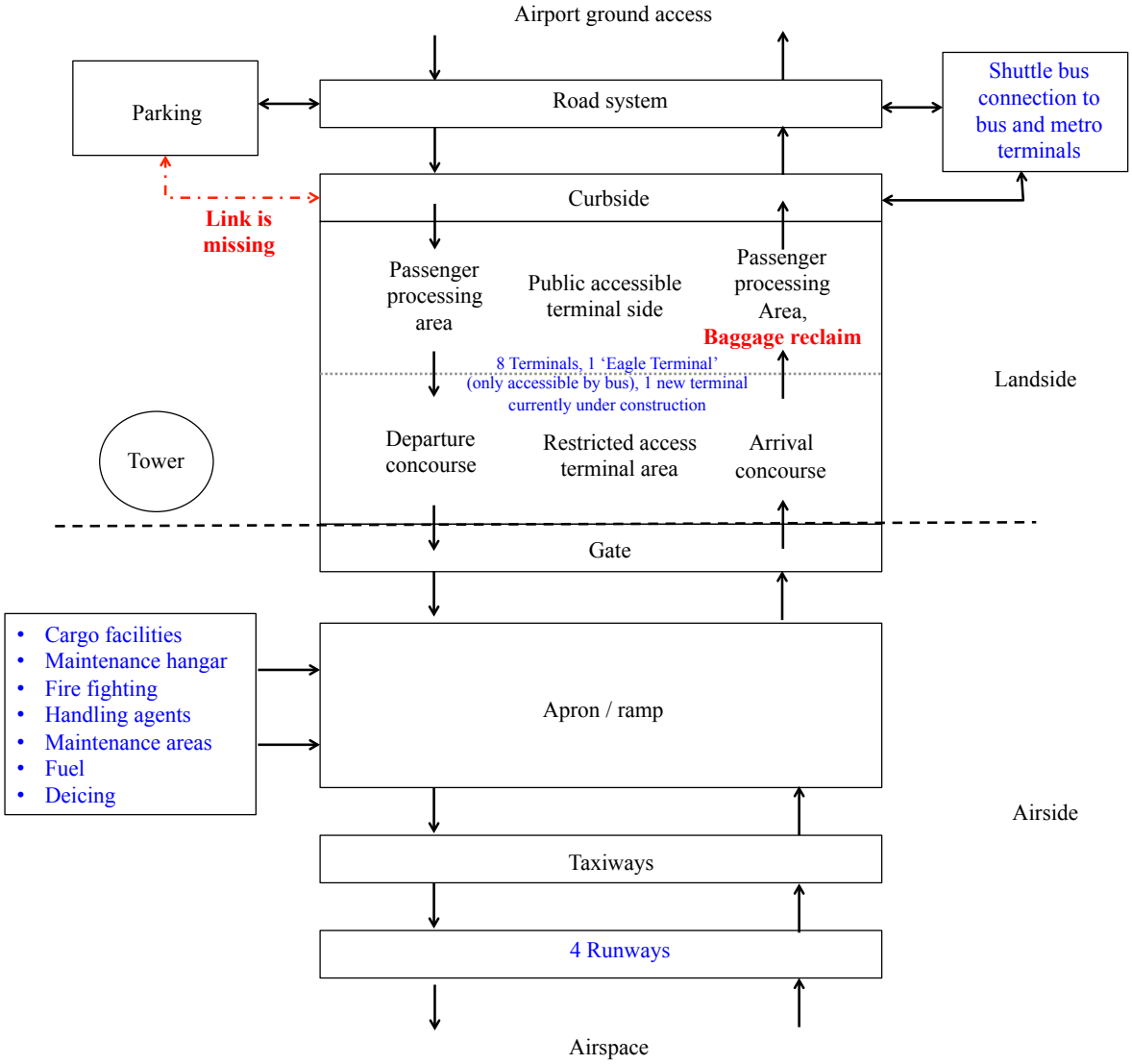


Figure 4: Components LAX

LAX's physical architecture resembles the model introduced in section 2.2.1. The airport has eight terminals and a further remote terminal, called the 'Eagle Terminal', which is connected to the main terminal through a bus service. Currently, only one gate can accommodate the Airbus A380 but a further terminal is under construction to accommodate the latest larger aircraft models. This development is urgently needed in order to accommodate the growing demand for A380's and similar large aircraft types and,

thus, to avoid losing business to other airports (Structured communication with Airfield Operations Superintendent Los Angeles World Airports, May 2012).

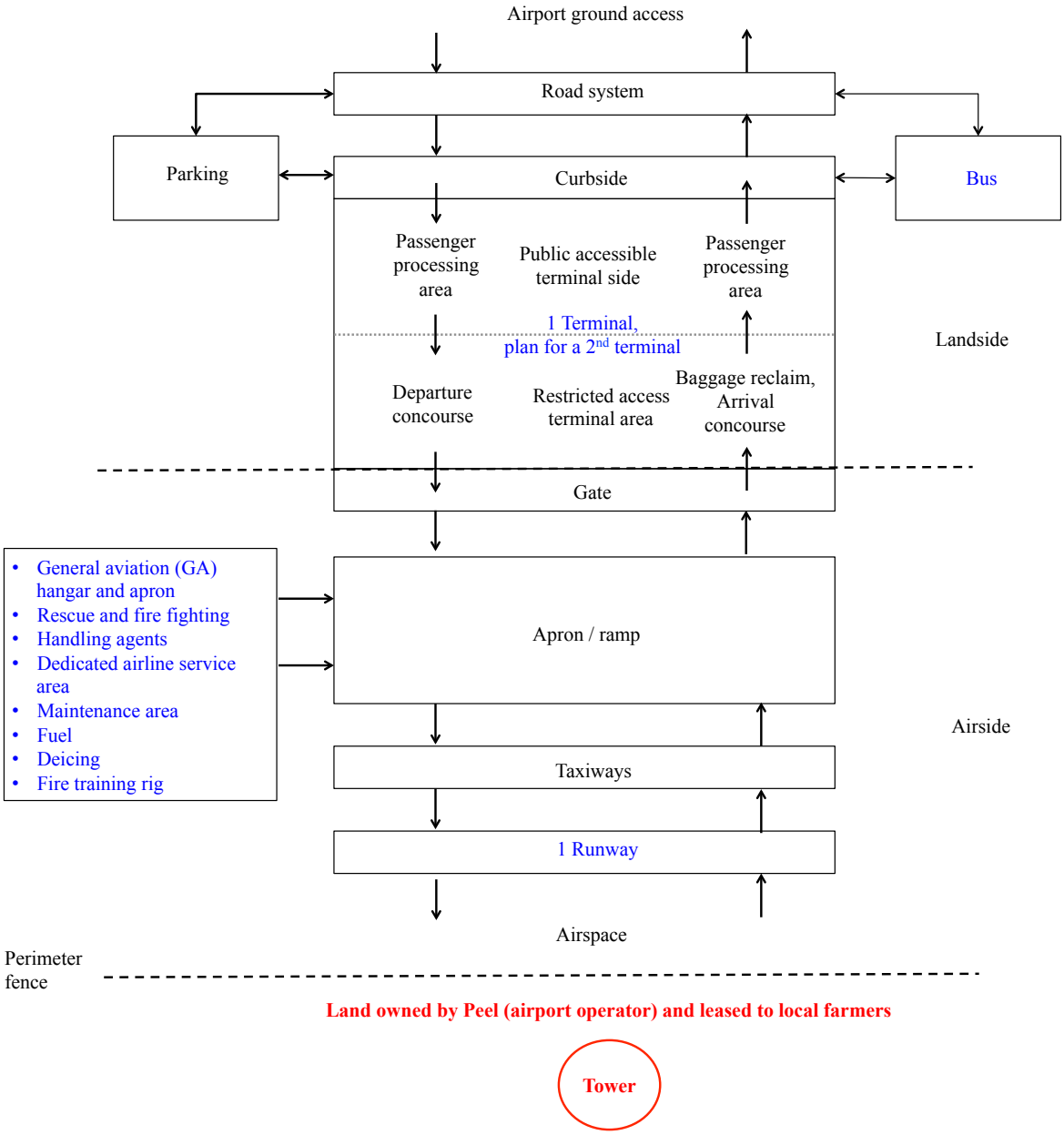


Figure 5: Components LPL

LPL's unique feature is the location of its control tower. Typically, the tower is located on the landside of an airport. Due to the historical development of LPL, the control tower is located outside the perimeter fence that separates the airport from its environment. The tower is separated from the airport by agricultural land that is owned by the airport operator and leased to local farmers. From this remote location, tower controllers monitor

the manoeuvring area from outside the airport (Structured communication with Head of Health Safety and Regulatory Compliance Peel Airports Limited, March 2012).

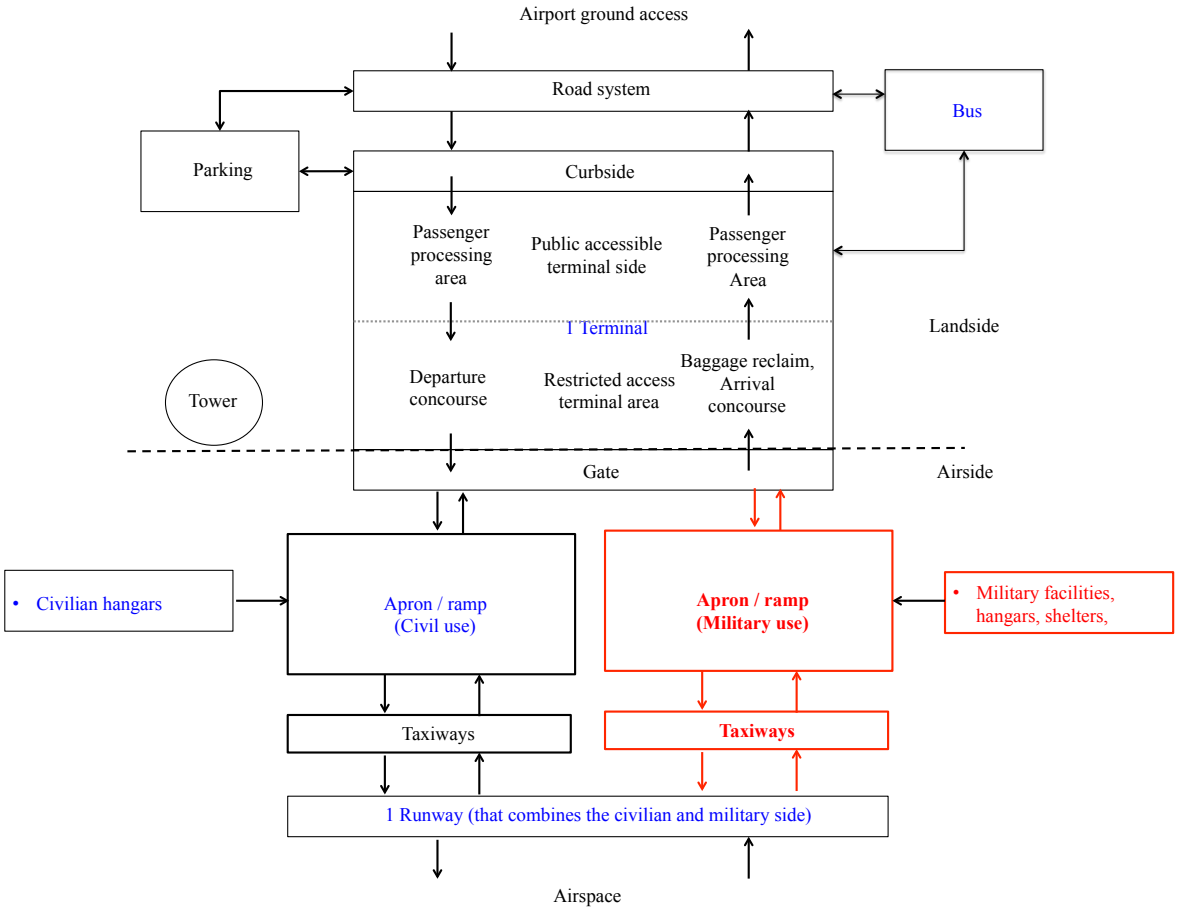


Figure 6: Components BOO

BOO differs from the other two airports mainly through its shared civil and military use (~80.0% civilian activities, 20.0% military activities). The airport has one runway, which combines both civilian and military areas. The passenger terminal and associated facilities are located on one side of the runway, while on the other side are the military facilities, hangars and shelters. Avinor, the airport operator, owns the terminals but the remaining airport infrastructure is owned by the Royal Norwegian Air Force (RNoAF) (Structured communication with ATC Tower Supervisor at Bodo Airport, June 2012).

The management and responsibilities of the different stakeholders in the airport activities also differ. Table 2 compares the three airports.

Table 2: Activities LAX, LPL, BOO

	LAX	LPL	BOO
1. Access facilities management:			
Parking	AA contractor	AA	AA
Shuttle services	AA contractor & PO	PO	n/a
Other transport services	PO	PO	PO
2. Terminal and passenger management:			
Service (e.g. public information)	Volunteers	Government (Local Council)	AA
Check-in	Airlines	Airlines	Airlines, Handling companies
Security	Government (TSA)	Outsourced to PO	Outsourced to PO
Sales	A vendor runs all concessions	POs	POs
Customs	Government (CBP)	Government (BC)	Government (NC)
Immigrations	Government (CBP)	Government (BC)	Police
Baggage facilities (infrastructure)	AA	AA	AA
Baggage flow management	Airlines, Handling companies	Handling companies	Handling companies
VIP assistance	AA, police	AA	AA
Mail and cargo processing	Airlines, Handling companies	AA	Handling companies, PO
3. Apron management:			
Gate / Stand allocation	Airlines, AA	AA	AA
Flight dispatch and ground handling	Airlines, Handling companies	Handling companies	Handling companies
Rules and regulations for airside operations	AA	AA	AA, RNoAF
Vehicle management	AA	AA	AA, RNoAF
Push-back operations	Handling companies	Handling companies	Handling companies
Taxi operations	Pilots	Pilots	Pilots
Visual aids maintenance / apron inspection and maintenance	AA	AA	RNoAF
4. Manoeuvring area management:			
Surface inspection and maintenance	AA	AA	RNoAF
Visual aids maintenance	AA	AA	RNoAF
Construction management	Coordinated by AA	Coordinated by AA	For terminal: AA, Other areas: RNoAF
5. Airside management:			
Air traffic and aeronautical information and communications services	ANSP/Regulator*	AA/ANSP**	ANSP
Radio navigation aids installations and maintenance	ANSP/Regulator	AA/ANSP	RNoAF is responsible, AA executed it
Wildlife hazard management	AA	AA	RNoAF
Obstacle control	AA	AA	RNoAF
Follow-me guidance and marshalling	AA	AA	RNoAF
Disabled aircraft removal	American Airlines is	Handling companies	RNoAF subcontracts

	the designated handler		to PO
6. General airport management:			
Aerodrome emergency planning	AA	AA	RNoAF
Rescue and fire fighting	City of LA	AA	RNoAF
Safety and security	APD	AA	AA, RNoAF
Slot negotiation and allocation	LAX is not slot controlled	AA, Airlines	AA
Cleaning, waste removal	PO	PO	AA, PO
Coordination with multi-agencies / dealing with stakeholders	AA	AA PR	AA, RNoAF
Public information (external)	AA PR	AA PR	AA, RNoAF

*The FAA is responsible for air traffic and aeronautical information and communications services. The FAA is an organisation providing both, ANSP and regulatory services.
**Peel, a private company, providing both, airport operator and ATC services.

Legend:
AA – Airport Authority
AA PR – Airport Authority Public Relations Department
APD – Airport Police Department
BC – Boarder Control
CBP – Customs and Boarder Protection
LA – Los Angeles
NC – Norwegian Customs
PO – Private Organisations
TSA – Transportation Security Administration

In terms of external stakeholders, all three airports interact with the stakeholders introduced in Figure 3. In addition, the government, local communities and suppliers are external stakeholders with interest in the studied airports. LAX is owned by the city of Los Angeles, LPL by a private company, and BOO is run by Avinor, a limited company wholly owned by the state. None of these airports, therefore, has external investors.

Based upon the three case studies, the physical and functional variability of airports was derived. This was achieved by comparing the architecture of LAX, LPL and BOO in terms of components, operations and stakeholders to the system architecture derived from the literature (presented in sections 2.2.1 to 2.2.3).

The results show that while the physical infrastructure of airports as well as its functionality (i.e. activities) does not differ, the implementation of these components and operations varies as follows:

Invariable airport characteristics:

- Basic airport components (except ground access system and apron facilities)

Variable airport characteristics:

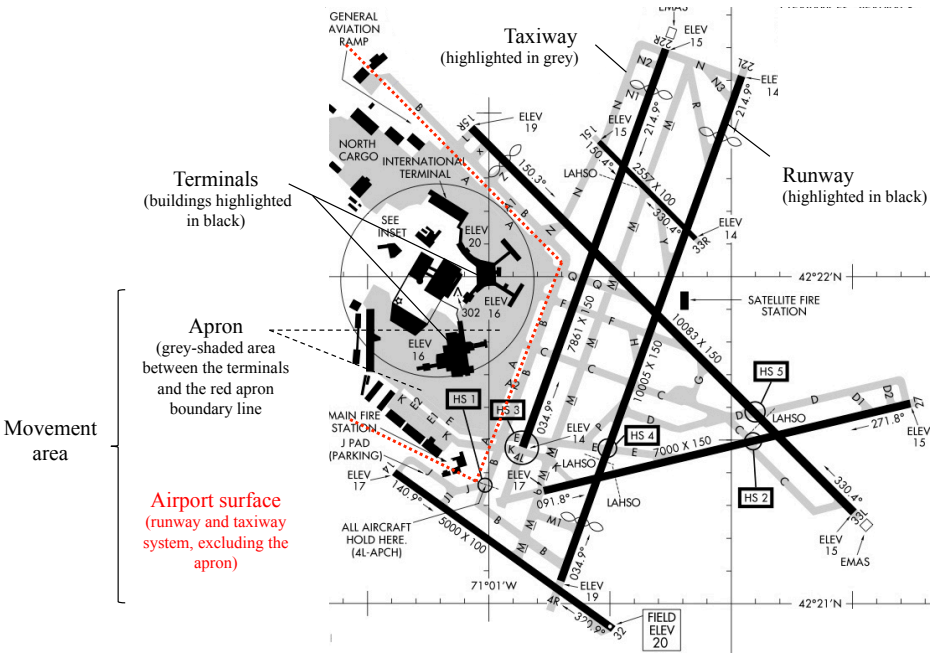
- Frequency of components
- Location of components
- Ground access system and airside facilities adjacent to the apron showed variable components

- Main airport activities
- External stakeholders of the air transport system
- Stakeholders responsibility for these activities
- Ownership structure

The operations of an airport can thus be summarised in one main function, i.e. the provision of a safe and efficient transition of passengers and goods between the ground and airspace. To achieve this function the operations on the airport surface, i.e. the physical location where this transition takes place, are crucial and, therefore, the next section moves on to introducing the central function of airport surface operations.

2.3 Surface Operations

In this thesis the *airport surface* is defined as the *manoeuvring area*, i.e. "the part of an aerodrome to be used for take-off, landing and taxiing of aircraft, excluding aprons" (International Civil Aviation Organization, 2004b). Both terms are used interchangeably throughout.



Source: Federal Aviation Administration National Aeronautical Charting Office (2011)

Figure 7: Airport surface

The airport surface comprises the runway and taxiway system within the manoeuvring area, highlighted in red in Figure 7. According to ICAO Annex 14 (2004b), a *runway* is defined as "rectangular area on a land aerodrome prepared for the landing and take-off of aircraft." A *taxiway* is defined as a "path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another […]."

The *apron* or *airport ramp*, an area "intended to accommodate aircraft for the purposes of loading or unloading passengers, mail or cargo, fuelling, parking or maintenance" is not considered in this research since the nature of operations here is quite different from that on the manoeuvring area. The manoeuvring area together with the apron is referred to as the *movement area*.

The airport surface accommodates the ground movements of aircraft. Inbound flights land on a runway and then use the airport surface to taxi to their assigned ramp at the apron, where ground handling takes place. Conversely, departure flights use the manoeuvring area to taxi from their ramp at the apron to an assigned runway for take-off. Thus, the airport surface is the physical location where the transition between the ground and airspace takes place.

Successful surface operations require the input and interactions of several stakeholders and the five main actors (airport operator, pilot, V/PD, ATC and regulator) are shown in Figure 8.

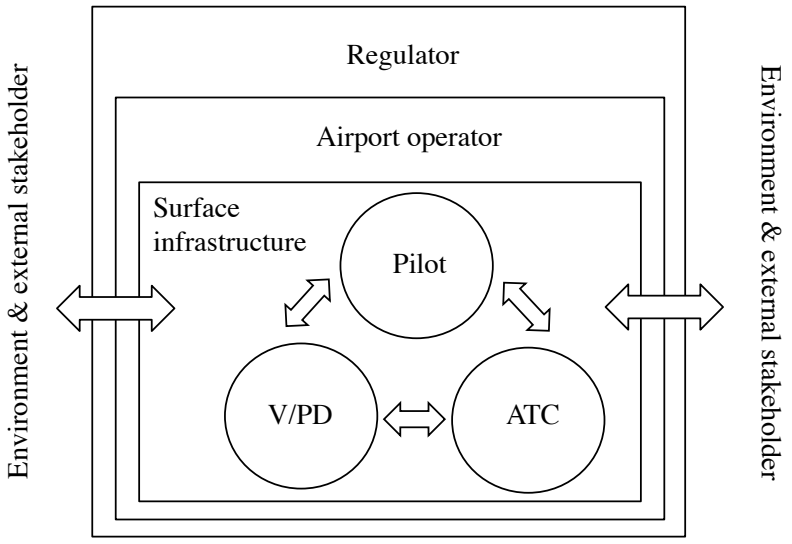


Figure 8: Airport surface actors

2.4 Key Performance Indicators

Airport performance is measured by means of Key Performance Indicators (KPIs) for corresponding specified Key Performance Areas (KPAs).

According to the ICAO, "KPAs are a way of categorising performance subjects related to high-level ambitions and expectations." KPIs are a quantitative measure for "current (or) past performance, expected future performance […], as well as actual progress in achieving performance objectives" (International Civil Aviation Organization, 2009d). Therefore, KPAs are defined according to an organisation's objectives (e.g. service-related, financial) with the quantification of performance enabled through the corresponding KPIs.

The ICAO provides guidance for performance management in ATM and recommends eleven KPA's including capacity, cost-effectiveness, predictability, safety, and security (International Civil Aviation Organization, 2005c). These have been completely or partially adopted by multinational cooperative bodies, and national regulators (e.g. Federal Aviation Administration, 2012c; Single European Sky ATM Research, 2012). The ICAO has also attempted to propose a globally standardised set of metrics and indicators (KPIs). It compared the eleven KPAs for two ATM organisations, but failed to identify common indicators due to different definitions of terms, fitting criteria (i.e. certain KPIs are only applicable to specific locations, times, etc.), normalisation of indicators, and statistical derivation (International Civil Aviation Organization, 2009d). In general, KPAs and KPIs can vary depending on the assessment objectives of an organisation and the system to be assessed (e.g. ATM system, airport and airline).

2.4.1 Airport Performance Measurement

For airports, the ICAO provides guidance on performance management and recommends that airports have a performance management system in place. Whilst the ICAO proposes that these systems should address the four KPAs productivity, cost-effectiveness, safety, and quality of service (International Civil Aviation Organization, 2009b), it has not directly proposed KPIs for airports. However, its 'Airport Economics Manual' (International Civil Aviation Organization, 2006c) proposes means of measuring

airport performance and productivity. More specific guidance for airport KPAs and KPIs is given by Airports Council International (ACI) (2012b).

Table 3 presents the main KPAs for airports and the corresponding KPIs for their measurement derived from ICAO, ACI and other regulatory bodies as well as safety organisations. In addition, the drivers of performance are shown. It should be noted that Table 3 is not exhaustive as there are other performance areas, measures, and drivers. Section 2.2.4 showed that the implementation of an airport's components and functions varies and as a result, individual airports will find different KPAs and KPIs to be most relevant and useful. For instance, privatized airports and non-profit government-owned airports are likely to focus on different financial KPIs. In addition, the airport management might have different views regarding which KPAs and KPIs are most useful. Whilst one manager might see a small set of closely monitored KPIs as the most effective performance management tool, others might prefer a larger set of KPIs with a wider focus. The KPAs and KPIs are also not static and can change over time as new issues arise (Airports Council International, 2012b).

The KPAs are not isolated areas; they either complement or contradict one another. For instance, airport core measures such as total number of passengers and aircraft movements influence the airport's revenue. On the other hand, safety / security and cost-effectiveness can be contradictory objectives, as effective safety solutions may increase airport operating costs.

Understanding these interdependencies is important to support decisions. For instance, airports must define their core KPIs and safety objectives and must balance these KPIs with acceptable safety risks. An airport might want to support its core KPA through an investment, for example, a taxiway lighting control system that provides guidance for aircraft from the runway to the apron by illuminating their particular taxi route. Decision making in this case requires assessing the trade-off between the value added by the system and the safety risks involved. If the investment is too high in order to make the system safe, it becomes unprofitable. On the other hand, an excess allocation of resources (i.e. money) to improve the airport's core KPIs at the expense of protection can have an impact on the airport's safety performance and lead to an accident. Therefore, understanding the interdependencies between safety, airport core measures and cost-effectiveness is vital and a prerequisite for decision making processes (International Civil Aviation Organization, 2009e).

Table 3: Airport KPAs, KPIs, and drivers

KPA	KPI	Driver
Airport core	• Total number of passengers • Total number of aircraft movements • Freight / mail loaded / unloaded	• Demand • Airline route planning and pricing • Competing airports in the same area • Capacity
Service quality	• Capacity - Terminal capacity - Gate capacity - Runway capacity • Aircraft turnaround time • Taxi time per aircraft • Delay - Percentage of delayed flights - Average aircraft delay - Gate departure delay • Customer satisfaction - Baggage delivery time - Percentage of lost luggage - Security clearing time - Border control clearing time - Connecting times	• Airport infrastructure • Staffing level and efficiency • Air traffic system restrictions • Weather and terrain • Network effects • Procedures • Aircraft type and mix • Airline scheduling practices
Productivity / cost-effectiveness	• Passengers per employee • Aircraft movements per employee • Cost per passenger • Cost per movement • Cost per ton of cargo • Cost per work load unit (WLU)	• Range of services provided by the airport • Extent of outsourcing • Passenger volume • Mix of air services provided (e.g. international, domestic) • Mix of carrier services provided (e.g. network vs. low cost carrier) • Airport operating costs • Management decisions
Financial / commercial	• Airport revenue • Revenue per passenger • Revenue per movement • Earnings before interest, taxes, depreciation and amortization (EBITDA) per passenger	• Rate making methodology • Costs for providing aeronautical facilities and services • Capital structure and spending • Demand • Airline route planning and pricing
Safety and security	• Number of accidents • Number of incidents • Public injuries • Occupational injuries • Lost work time from employee due to accident / incident	• Airport surface design • Operations and maintenance • Meteorological conditions • Operator errors • Unsafe working conditions • Lack of safety culture
Environment	• Airport carbon footprint • Emissions per aircraft • Noise quota • Number of noise level infringements • Utilised energy	• Emissions • Power usage • Noise restrictions • Management actions

Sources: Airports Council International (2012b); ERAT Environmentally Responsible Air Transport (2008); Federal Aviation Administration (2012c); International Civil Aviation Organization (2005c, 2006c); The European Organisation for the Safety of Air Navigation (2009)

2.4.2 The Importance of Safety

One key performance area for airport operations is safety, the subject of this thesis. It is one (in addition to security and environmental protection and sustainable development of air transport) of the ICAO's strategic objectives "to foster a global civil aviation system that consistently and uniformly operates at peak efficiency and provides optimum safety, security and sustainability" (International Civil Aviation Organization, 2012). The ICAO defines safety as "the state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management" (International Civil Aviation Organization, 2009e).

The concept of safety involves different connotations, such as:

- Zero accidents or serious incidents;
- Freedom from hazards, i.e. those factors that cause or are likely to cause harm;
- Attitudes of employees of aviation organisations towards unsafe acts and conditions;
- Error avoidance; and
- Regulatory compliance (International Civil Aviation Organization, 2009e).

Independent of the connotation, however, safety is the most fundamental strategic objective in aviation (International Civil Aviation Organization, 2011a). The previous section 2.4.1 highlighted that safety objectives interact with other KPAs. However, before these trade-offs can be considered, the fundamentals of safety need to be understood. Therefore, this thesis focuses on the safety assessment of airport operations, and in particular the operations on the airport surface.

2.5 Airport Surface Safety

Section 2.3 introduced the central role of surface operations. Because of the complexity of aircraft and the associated complex system of activities of stakeholders, airport surface operations are vulnerable to safety lapses.

In this thesis, and in line with the ICAO's general definition, *airport surface safety* refers to a prevailing situation on the airport surface that does not cause any harm or injury

to both the property (e.g. aircraft, vehicles, airport infrastructure) and people (aircraft occupants, vehicle drivers, pedestrian) directly involved in surface movements, and any third parties (people and property outside the manoeuvring area) and property (e.g. terminal, residential areas) outside the manoeuvring area. A situation in which safety is compromised is referred to as a safety *occurrence.*

Airport surface safety occurrences can take various forms. Examples include situations where an aircraft, vehicle or person infringes onto a runway that already has another aircraft waiting to take-off or moving towards its stand at the terminal; in effect, a near-collision between aircraft and another object on the ground. Other surface related safety occurrences are runway excursions where an aircraft exits the end or side of the runway surface; wildlife hazards such as bird strikes; or foreign object damage (FOD). A major feature of airport surface safety is that the key drivers of such safety, e.g. airport geometry, weather and human factors, interact in a complicated manner.

The need for safety mitigation measures has been increasingly recognised over recent years, leading to a steady stream of initiatives and action plans. Previous initiatives have addressed the topic of surface safety from different viewpoints including technological interventions, regulations and actions that target the improvement of human performance, e.g. advanced training programmes or awareness campaigns. These initiatives operate at different levels and involve a variety of organisations and industries, including regulators (e.g. International Civil Aviation Organization, 2007), ANSPs (e.g. Federal Aviation Administration, 2010d), airport operators (e.g. BAA Heathrow, *et al.*, Year not specified), multinational aviation safety organisations (e.g. Flight Safety Foundation, 2009; The European Organisation for the Safety of Air Navigation, *et al.*, 2011), research institutions (e.g. National Aeronautics and Space Administration (NASA) (Bluck*, et al.*, 2001)) and aircraft manufacturers (e.g. Airbus, 2009).

The current approach to surface safety, however, is ad-hoc and piecemeal and its limitations have been highlighted in Chapter 1. These are:

- The focus on single accident / incident types, often particular scenarios;
- The representation of single stakeholder perspectives; and
- Methodological limitations including ambiguous or missing definitions, insufficient specification of safety data and data quality concerns (e.g. data accuracy), and unspecified analysis methodologies.

Although the current focused approach is understandable given the different responsibilities and interests of the involved stakeholders, it cannot be sufficient, since the safety enhancement strategies that are developed through this approach are inevitably biased or limited by the particular perspective of the particular stakeholder. There is an urgent need for a holistic and robust safety assessment of airport surface operations that integrates the viewpoints of all relevant aviation stakeholders in the context of surface safety (regulator, airport authority, pilot, ATC, ground handling) and this thesis seeks to address this need.

2.6 Summary

This chapter has developed a descriptive model of the airport architecture including its components, functions and stakeholders and identified its variability. In addition, key performance areas and indicators have been defined and the importance of safety highlighted. In particular, the central role of surface operations and safety implications have been emphasised and the vulnerability associated with the complexity of infrastructure and operations, discussed. In order to ensure the safety of surface operations and to contribute to the mitigation of accidents and incidents, this thesis develops a framework for a holistic assessment of airport surface safety.

The principal conclusion of the review and analysis conducted in this chapter and contribution is that while the physical architecture of airports and their functionality is always the same, the implementation of these components and activities varies. With this, the first research objective has been achieved.

After having defined the static architecture of airports, the next chapter addresses the dynamics of its operations and develops a process model of airport surface operations.

3 Airport Surface Operations

The previous chapter defined the static architecture of airports and highlighted the central role of surface operations and their vulnerability. Building upon this architecture, the current chapter models the airport's dynamics, i.e. the process of its operations. A detailed understanding of the airport surface operations, including its complexities, is essential before its safety can be analysed. Therefore, and to address the second research objective, a 4-dimensional process model of airport surface operations is developed. This model will guide the development of the airport SMS in this thesis.

The chapter starts with a high-level description of the methodology for model development highlighting the objectives and assumptions, and introduces the concept of Business Process Modelling. This method is used in this thesis as the framework for analysing and improving the process of surface operations. Subsequently, the method for derivation and implementation of the Business Process Model (BPM) is elucidated in detail. Individual models are developed for the physical airport surface infrastructure, the airport operator, pilot, V/PD, ATC, and the regulator. Furthermore, the interfaces between the individual parties are highlighted. The components are then integrated in a high-level architecture of the overall airport surface system, which is a necessary prerequisite for SMS development. Finally, the effect of time on the process of surface operations is analysed and time variant and invariant characteristics of such processes derived.

3.1 Methodology

In order to develop an initial process model (PM) of normal operations, it is necessary to outline what is meant by normal. In this thesis 'normal operations' refer to airport surface operations that satisfy the following:

- Aircraft, vehicles and ATC equipment are not subject to malfunctions;
- The aeronautical infrastructure (including airport surface infrastructure) that is needed for normal operations is not subject to malfunctions;
- There are actors (i.e. pilot, V/PD, ATC) that interact for successful operations;
- The actors have the adequate level of training and are fit to carry out their work;
- Environmental conditions do not exceed the capabilities of the airport and its actors; and
- Airport operations are operations undertaken to an acceptable level of safety.

The PM of normal airport surface operations is developed using the conceptual framework of Business Process Modelling as outlined below. To develop the Business Process Model (BPM) the Unified Modelling Language (UML) is applied and individual models that describe the physical surface infrastructure and the operations of the five main stakeholders, as well as their interfaces are developed. To establish the UML model, Hierarchical Task Analysis (HTA), a systematic method of describing the tasks an operator needs to carry out to complete his / her operation (Kirwan and Ainsworth, 1992), is applied. HTA requires the input of several data sources and, therefore, a hybrid methodology that combines the literature with an analysis of operations manuals and procedures, together with observations and structured communications with airport operational personnel is applied. The individual models are then integrated resulting in the high-level architecture of the airport surface system, which is finally validated through Subject Matter Experts (SMEs).

3.1.1 Business Process Modelling

Business Process Modelling is a management tool for improving organisational efficiency and quality. The Business Process Model (BPM), whose central features is diagrams and an appropriate modelling language, is used to model, analyse, and identify

deficiencies and improve or optimise business processes (Havey, 2005; Holt, 2009; White and Miers, 2008). It is a graphical representation of the business process, also known as 'notation'. In the broadest sense, a BPM is one or more diagrams representing a sequence of activities underlying organisational processes. These activities can be modelled at different levels of detail and, depending on the modelling objectives and model requirements may include, actors, events, activities, associations and information flows (Havey, 2005; Holt, 2009; White and Miers, 2008).

Business Process Modelling can be applied to all types of organisations and industries (e.g. clinical research (Leu and Huang, 2011; Scheuerlein*, et al.*, 2012)) and has been successfully employed in aviation (e.g. airline business process models (Ploesser*, et al.*, 2009), passenger check-in models at airports (Lincoln*, et al.*, 2010)).

In this thesis, Business Process Modelling is employed to model, analyse and improve the safety of airport surface operations. The first step in this process is to develop a BPM of normal surface operations, which can subsequently be analysed for process failures. Effective safety enhancement strategies can then be proposed based on this initial model.

To develop the BPM, a modelling language needs to be applied and the Unified Modelling Language (UML) was used in this research as outlined below.

3.1.2 Unified Modelling Language

Unified Modelling Language (UML) is a visual modelling language that is used to create a model of a system. It has its roots in object-oriented software engineering and is mainly used for system (e.g. software) development. System development is a drawn-out process involving the definition of requirements, an in-depth analysis of existing business processes, design, development and deployment. UML supports this process by providing a toolkit that allows the various elements of the current system to be visualised, the requirements for the system to be developed, and associations between the different elements to be made. Although UML was developed for the Information Technology (IT) industry, it has been applied to various areas, including the analysis of conventional business processes (Schmuller, 2009).

In addition to UML, there are numerous languages for process modelling. Whilst most of them represent processes as a series of steps, they emphasize different aspects of the

process, such as activities, products, or document and information flows. Hence, they are suited for different types of processes.

The aim of this chapter is to describe the physical architecture of the airport surface as well as the operations of the stakeholders, i.e. the tasks each actor needs to carry out to complete his / her operation. Therefore, a modelling language that focuses on the flow of activities is required. Three examples often used in Business Process Modelling, which support activity modelling, are the Business Process Model and Notation (BPMN), UML, and the System Modelling Language (SysML). These have been developed for different applications and BPMN is mainly used for business analysis, UML for software development, and SysML for system engineering. Irrespective of their proposed applications, the execution of the activity diagrams in the notations is very similar and differs mainly in their terminology and graphics (Bock, 2006; International Business Machines Corporation, 2013; Schmuller, 2009; White, Year not specified). For example, Figure 9 shows the notation used in the three languages to model activity flows.

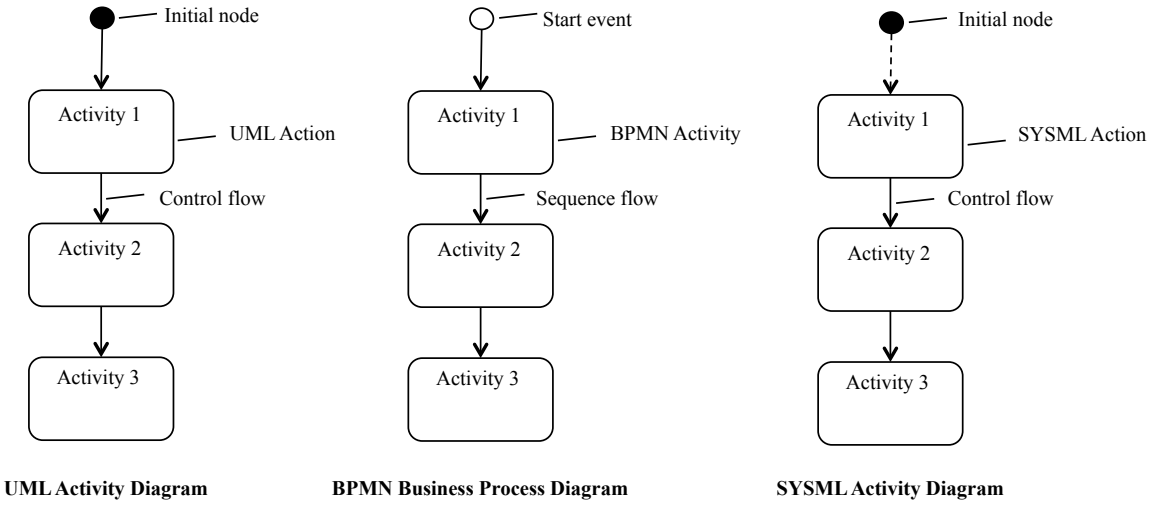


Figure 9: UML, BPMN, SysML notations for activity flows

Despite different notations, the three languages are conceptually the same. Thus, any of the three modelling languages would be suitable for modelling the flow of activities of the airport surface stakeholders. Furthermore, research has shown that there is no difference in the ease of use of the three languages (Peixoto*, et al.*, Year not specified). Therefore, the decision to use UML in this thesis was made on the basis of the availability of the required software.

The basic feature of UML is diagrams. A UML diagram consists of a number of graphical elements linked according specific rules. The purpose of these diagrams is to represent multiple viewpoints of a system. The set of UML diagrams that represent multiple views of a system is called a *model* and four main categories of diagrams for model development can be distinguished: structure modelling, use case modelling, behavioural modelling, and architectural modelling. These are introduced in Appendix I in detail as outlined in Schnuller (2009).

3.1.3 Method for Derivation of a Business Process Model

The method to develop the BPM comprises the introduction of the terminology using a class diagram and, subsequently, the development of individual models for all relevant classes as follows:

- Model of the physical infrastructure of the airport surface;
- Model of the role of the airport operator;
- Model of normal pilot operations;
- Model of normal V/PD operations;
- Model of normal ATC operations;
- Model of the role of the regulator; and
- Model of interfaces.

These models are then integrated in a high-level architecture showing the overall airport surface system.

Firstly, the physical airport surface infrastructure is modelled using a class diagram in aggregation form, which is used to represent hierarchies of classes. A class is " a category or group of things that have similar attributes and common behaviours" (Schmuller, 2009).

In the second step, the role of the airport authority in managing and maintaining the airport surface is defined. Only the responsibilities of the airport authority are introduced. Since airport authority personnel operate on the airport surface in the form of vehicles and pedestrians, details of how these responsibilities are executed (i.e. a detailed account of the elements and subtasks involved) can be seen in the model of V/PD operations, which is developed subsequently. The role of the airport authority is summarised using a package diagram. This type of diagram is designed to group elements (e.g. classes).

In the third step, the operations of the three stakeholders that directly act and interact on the airport surface (i.e. pilot, V/PD, ATC) are modelled. The aim is to understand the tasks and sub-tasks that the stakeholders must perform as part of their operations.

To develop the UML, Hierarchical Task Analysis (HTA) is applied. As specified, e.g. in Kirwan and Ainsworth (1992), this is a systematic method of describing how work is organised in order to meet the objective of the operation. It is a top-down approach, which starts by identifying the overall goal of the operation (objective). This operation is subsequently broken down into sub-operations (phases), which are accomplished through a series of tasks. In addition, the necessary resources for task accomplishment (i.e. actors that are required for task accomplishment) are defined.

To achieve a detailed understanding of the tasks the stakeholders perform it is desirable to incorporate as many sources of information as possible. This includes documentation, manuals for maintenance and operating procedures, the opinion of experts, operators, instructors and managers, as well as observations. When carried out correctly, HTA provides an exhaustive analysis of the problem addressed. This systematic deconstruction of the operation provides a picture of the tasks undertaken by each of the actors in normal conditions, and can be continued until the desired level of detail is reached. A further advantage of HTA is that it is a generic method adaptable to a wide range of purposes, and indeed, has been successfully applied in aviation research (e.g. Nascimento, 2011; Soekkha, 1997; Walker*, et al.*, 2005). One difficulty though is that HTA is both resource and time intensive, requiring a variety of data collection methods. In addition, the full collaboration of the relevant stakeholders is necessary (Kirwan and Ainsworth, 1992; Stanton*, et al.*, 2005).

Alternatives to HTA that can be used to analyse what an operator is required to do to achieve a goal include, for example, charting and networking techniques, decomposition methods, operational sequence analysis and timeline analysis. Flow charts and network diagrams are graphical representations of tasks. An important aspect of these techniques is that many of them represent not only human tasks, but also system elements (e.g. equipment involved, material flows) and, therefore, they are mainly used for displaying the human role embedded within the system context.

Decomposition methods are used to systematically expand upon the basic description of activities undertaken by a stakeholder. Thus, they are a structured way of expanding the information produced, e.g. by HTA, into a series of more detailed statements. For each task element that is of particular interest to an analyst, further information about specific

aspects of the tasks (e.g. the time taken for that task element to be completed, the nature of the equipment that is used) is gathered and then presented for each task element. This allows the decomposition of tasks into a series of statements about limited aspects of the tasks.

In their simplest form, operational sequence diagrams are flow diagrams that link the various tasks in the order they are normally carried out. The disadvantage of these diagrams is that they can become confusing when used for complex tasks. Finally, timeline analysis requires the analysis of both the functional and temporal requirements that a human operator needs in order to complete a task. Timelines are representational techniques and heavily reliant on input from other techniques for gathering the basic input information, e.g. HTA to break down an operation into tasks and sub-tasks, before assigning the time scales. As they consider temporal relationships, they are primarily used to aid in allocating tasks between operators, or operators and machines (Stanton*, et al.*, 2005).

After considering the advantages and disadvantages of the above techniques in relation to the aim of modelling the tasks stakeholders must perform, as well their historical applications, HTA was evaluated as being the most suitable.

Using HTA, separate models for each of the three actors (pilot, V/PD, ATC) are developed. This is necessary given that any single model would always take on a specific viewpoint. A high-level task analysis is carried out for each of the three actors in order to deconstruct their operations into meaningful phases and the tasks which need to be carried out in each of these phases are defined. In order to keep the model to a manageable size limits for task deconstruction are defined in relation to:

- Aircraft model;
- Procedures at a company level (airline, airport, ANSP); and
- Tasks of V/PD allowed on the airport surface.

Whenever further task deconstruction would require analysis of sub-tasks such as tasks specifically applicable to a single aircraft model, a specific task of V/PD, or to reflect the procedures of a given company deconstruction would stop.

Subsequently, the actors that are required to accomplish the necessary tasks in each phase are identified. Two types of actors could be distinguished: direct actors and indirect actors. This distinction is based on Reason's concept of active failures and latent conditions (Reason, 1997). Reason describes active failures as unsafe acts that "are likely

to have a direct impact on the safety of the system". Active failures are errors or violations committed by people directly involved in the operations (e.g. pilots, ATC). Latent conditions (e.g. poor design, undetected manufacturing detects, gaps in supervision), on the other hand, are factors that lie dormant in the system and which may be present for many years before they facilitate, or contribute to an occurrence (e.g. design failure).

The corresponding UML notation used state diagrams to model the task-deconstruction. State diagrams reflect the state of single objects and allow for the modelling of all the changes the object goes through. The detailed task analysis for pilots and V/PD is subsequently represented using activity diagrams. Activity diagrams are chosen because they show the steps, i.e. activities, in an operation and this chapter aims to model the process of tasks necessary for the successful completion of an operation. To this end, the concept of swimlanes that are used to dissect an activity diagram into parallel lanes showing the activities for each actor is adapted. Here, swimlanes were used to highlight the geographical location in which the tasks are accomplished. This consideration of spatial effects will later help to identify how failures in the process of one actor's operation can affect the operations of the other stakeholders. Finally, the actors that influence the operations are summarised using class diagrams.

The UML notation for ATC operations is slightly different to that described above. Since ATC operations are multi-tasking operations, the activities cannot always be modelled in a pre-defined sequence. Activity diagrams showing the sequence of tasks seemed inappropriate and, consequently, a package diagram is employed. As above, however, the actors influencing ATC are summarised using a class diagram.

After having developed detailed operational models for the three actors directly involved in surface operations (i.e. pilot, V/PD, ATC), the role of the regulator is defined in the fourth step. A package diagram summarises the regulator's responsibilities.

Fifth, the interfaces between the actors are highlighted using interface diagrams. Finally, based on the developed models; the high-level integrated architecture of surface operations, i.e. the *airport surface system*, is derived. The model is unique, as it is the first integrated airport surface operations model to represent the interaction of all relevant stakeholders and the physical airport surface infrastructure.

3.1.4 Implementation of the Method

Since HTA requires the input of various sources of information, a hybrid methodology has been applied to develop the initial process model in four steps:

1) Review of the relevant literature and existing airport models (e.g. Ashford*, et al.*, 1997; deNeufville and Odoni, 2003; Dupuy, 2012; Horonjeff and McKelvey, 1994; Institution of Civil Engineers, 1967; Janic, 2008; Kazda and Caves, 2000; Subotic, 2007; Wells, 1996); and
2) Analysis of operations manuals (e.g. easyJet plc, 2010a, c), standards and procedures (e.g. International Civil Aviation Organization, 2001a, 2004a, b, 2005a, b, 2006b, e).

Based on the review of the literature and the analysis of operations manuals initial UML models were developed for each stakeholder. These models were subsequently refined using observations and structured communications with operational personnel as outlined below.

3) Observations and structured communications:

- Three pairs of pilots were observed during six jump seat flights (i.e. outbound and inbound flight per pair of pilots). The initial model of pilot operations was used as a baseline and it was observed whether the pilots acted according to the model proposed. The first flight (i.e. outbound) was used each time purely to observe the pilots. During the second flight (i.e. inbound) the pilots were questioned as to when and why they did a certain task. In addition, the pilots explained more general issues (e.g. instruments and computer systems in the cockpit, documentation on board) that helped to clarify their operations and responsibilities. Based on these inputs the initial process model was refined (e.g. tasks were added, task sequence was changed).
- Likewise, pairs of ATC Tower controllers were observed at Gatwick Airport, Boston Logan International Airport and Oslo Lufthavn. The choice of these airports is explained in the next paragraph. Each position (i.e. planning and tactical controller) was observed for 15 minutes. The initial ATC model was used as a reference and it was observed whether the ATC operations conform to the proposed model. Subsequently, the tower supervisors at each airport explained in detail the tasks of ATC and the initial UML was refined using these inputs.
- Finally, observations at Heathrow Airport, Gatwick Airport, Boston Logan International Airport, Manchester Boston Regional Airport, Oslo Lufthavn and structured communication with airport authority operational personnel were

conducted. These included airfield tours and structured communications with Airfield Superintendents (i.e. supervisors) that followed the same methodology introduced in Chapter 2 section 2.2.4. In addition, other operational personnel were questioned on an ad-hoc basis about their tasks and responsibilities (e.g. construction workers, wildlife management personnel) in order to better ascertain the functionality of general airport operations. At Heathrow Airport the turn-around processes of several aircraft were observed and the Safety Manager of a ground handling company explained in detail the tasks of the various parties involved. Ad-hoc communications with operational personnel on the apron helped further to understand the role of ground handling. The observations spanned over a whole day at each airport in order to cover both, peak and non-peak, hours.

- The airports used as inputs for the model development were chosen to fulfil the following criteria:
  - Mixture of airports in North America and Europe building on Chapter 2's indication of operational differences, and
  - Medium to large airports in terms of movements and passenger boarding to ensure that a sufficient number of operations take place during the observation period (e.g. small airports may only have very few and isolated operations per day). The model fit was later tested on small airports.

Following the model development the UMLs were validated internally as described below.

4) Internal validation of the developed UML models with Subject Matter Experts (SMEs):

- Airfield Operations Shift Supervisor of a U.S. airport operator,
- FAA Line Manager / Tower Supervisor,
- Chief Pilot of a U.S.-based airline.

The SMEs were located at the airports used for the model development. All SMEs had at least 15 years of relevant experience in their particular area and were in senior positions. The experts were asked to systematically assess the UMLs and to comment on their validity. This process led to small corrections, such as the re-ordering of tasks.

The initial PM is developed further in Chapter 8, where safety data is used to define the stochastic elements in the model. Furthermore, to assess the model fit, the PM is validated externally and the details are specified in Chapter 9. Chapter 9 also contains the final

model. Figure 10 summarises the methodology underlying the development of the process model.

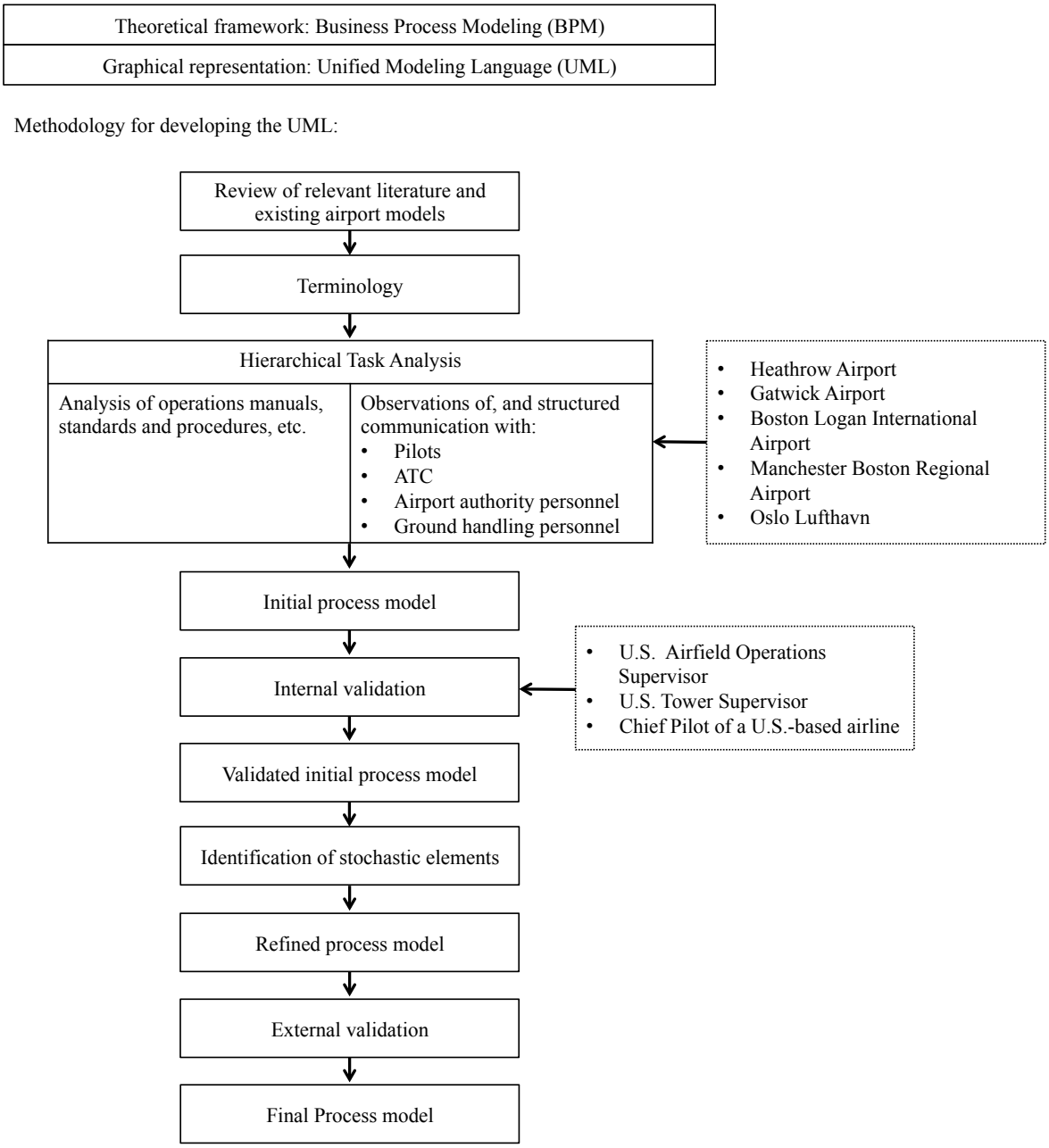


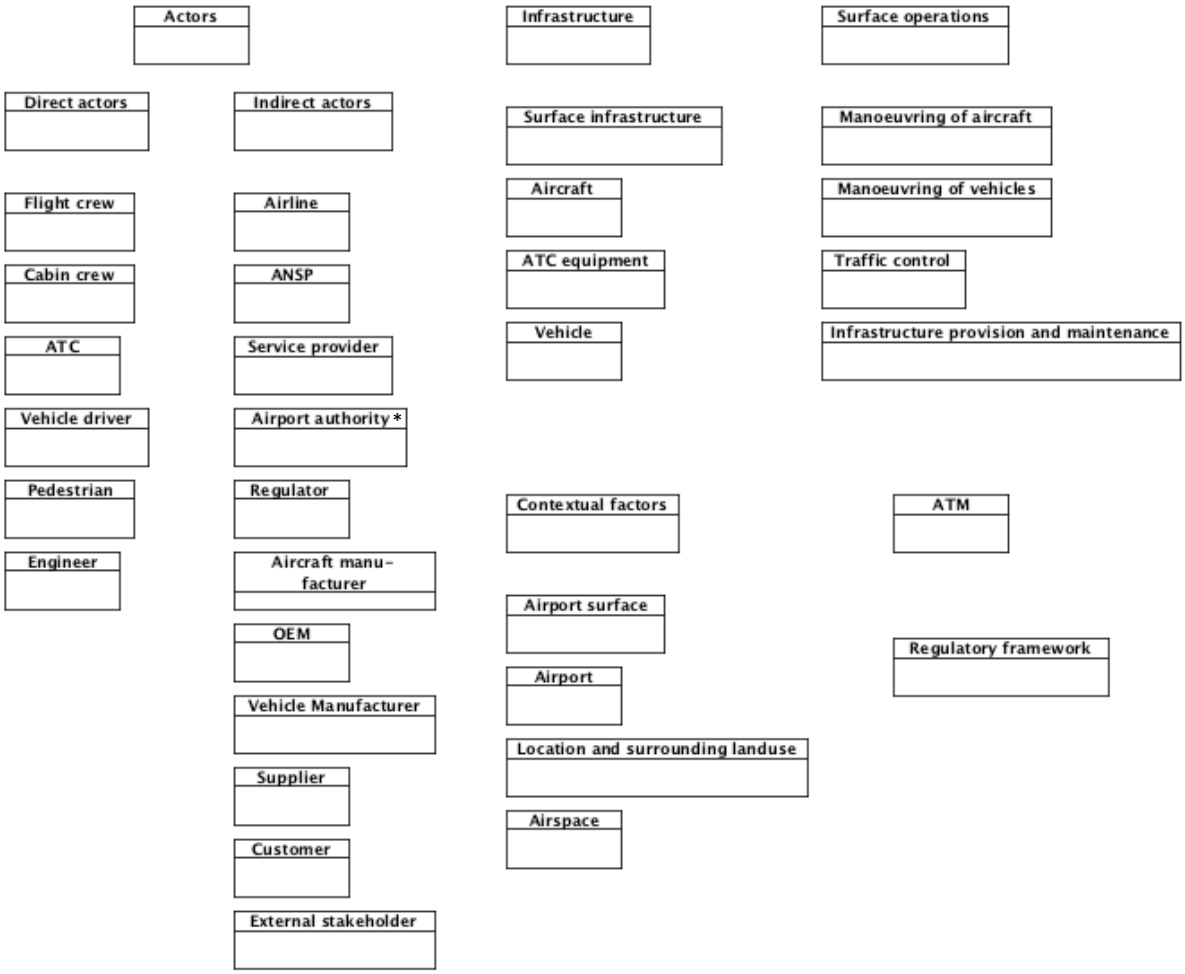
Figure 10: Methodology for the development of a process model of airport surface operations

3.2 Process Model of Normal Airport Surface Operations

The following sections introduce the initial process model developed based on the methodology specified in sections 3.1.3 and 3.1.4.

3.2.1 Terminology

To provide an overview of the subject matter a class diagram (Figure 11) has been developed. Since the airport surface is a complex environment with numerous associations, the class diagram aims to introduce the terminology, i.e. classes, only. Associations between the classes are derived subsequently.



* The airport authority can be a direct and an indirect actor. As direct actor the airport authority appears in form of vehicle drivers and pedestrians on the airport surface. As operator of the airport in general terms it acts as indirect actor.

Figure 11: Airport surface operations - terminology

3.2.2 Physical Infrastructure

The physical airport surface infrastructure comprises the runways and taxiways and associated safety areas, other surface areas (e.g. grassland that separates the surfaces), electronic and visual navigational aids (NAVAIDS) that assist aircraft in determining their position, data collection devices (e.g. weather), radio transmission devices and other surface infrastructure.

Basic elements, such as the runways and taxiways and their associated lights, signs and markings, can be found at all airports. The configuration of electronic NAVAIDS on the other hand is runway specific and dependent on the approach category and applicable flight rules. Two types of flight rules can be distinguished: Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). VFR apply in Visual Meteorological Conditions (VMC) that are "meteorological conditions expressed in terms of visibility, distance from cloud, and ceiling, equal to or better than specified minima" (International Civil Aviation Organization, 2005b). IFR apply in Instrument Meteorological Conditions (IMC), i.e. "meteorological conditions expressed in terms of visibility, distance from cloud, and ceiling, less than the minima specified for visual meteorological conditions" (International Civil Aviation Organization, 2005b).

Based on the flight rules, three types of approach can be distinguished as follows:

- Visual approach: "An approach when either part or all of an instrument approach procedure[1] is not completed and the approach is executed with visual reference to the terrain" (The European Organisation for the Safety of Air Navigation SKYbrary, 2012d);
- Non-precision approach: "An instrument approach which utilises lateral guidance but does not utilise vertical guidance" (International Civil Aviation Organization, 2005b); and
- Precision approach: "An instrument approach using precision lateral and vertical guidance with minima as determined by the category of operation" (International Civil Aviation Organization, 2005b). There are five categories of precision approach and landing operations: CAT I, CAT II, CAT IIIA, CAT IIIB, and CAT IIIC. They are defined according to the applicable decision height (DH), runway

[1] Instrument approach procedure: "A series of predetermined maneuvers for the orderly transfer of an aircraft under instrument flight conditions from the beginning of the initial approach to a landing or to a point from which a landing may be made visually" (Federal Aviation Administration, 2012d)

visual range (RVR), and visibility (The European Organisation for the Safety of Air Navigation SKYbrary, 2012a).

While visual approaches do not utilise electronic NAVAIDs, instrument approaches utilize non-precision approach systems (e.g. Very High Frequency (VHF) Omnidirectional Range (VOR), Nondirectional Beacon (NDB)) and precision systems (e.g. Instrument Landing System (ILS), Microwave Landing System (MLS)) providing lateral, and / or vertical guidance.

Electronic NAVAIDs are complemented by visual NAVAIDs. Approach Lighting Systems (ALS), for instance, are lighting systems that provide visual guidance for landing aircraft and typically serve runways operating instrument approach procedures. The configuration of the ALS is dependent on the instrument approach category. Likewise, different Visual Glide Slope Indicator (VGSI) systems exist (e.g. Visual Approach Slope Indicator (VASI), Precision Approach Path Indicator (PAPI)) and provide visual descent guidance to help landing aircraft maintain the glide path during their approach to the runway. Other visual NAVAIDs such as Runway Status Lights (RWSL) or Final Approach Runway Occupancy Signal (FAROS) can also be found on the airport surface.

Finally, other surface infrastructure, such as radar, Engineered Material Arresting Systems (EMAS), ship radar, or automated FOD detection systems, may be present at some airports. The physical infrastructure can be modelled using a class diagram in aggregation form as outlined in Figure 12.

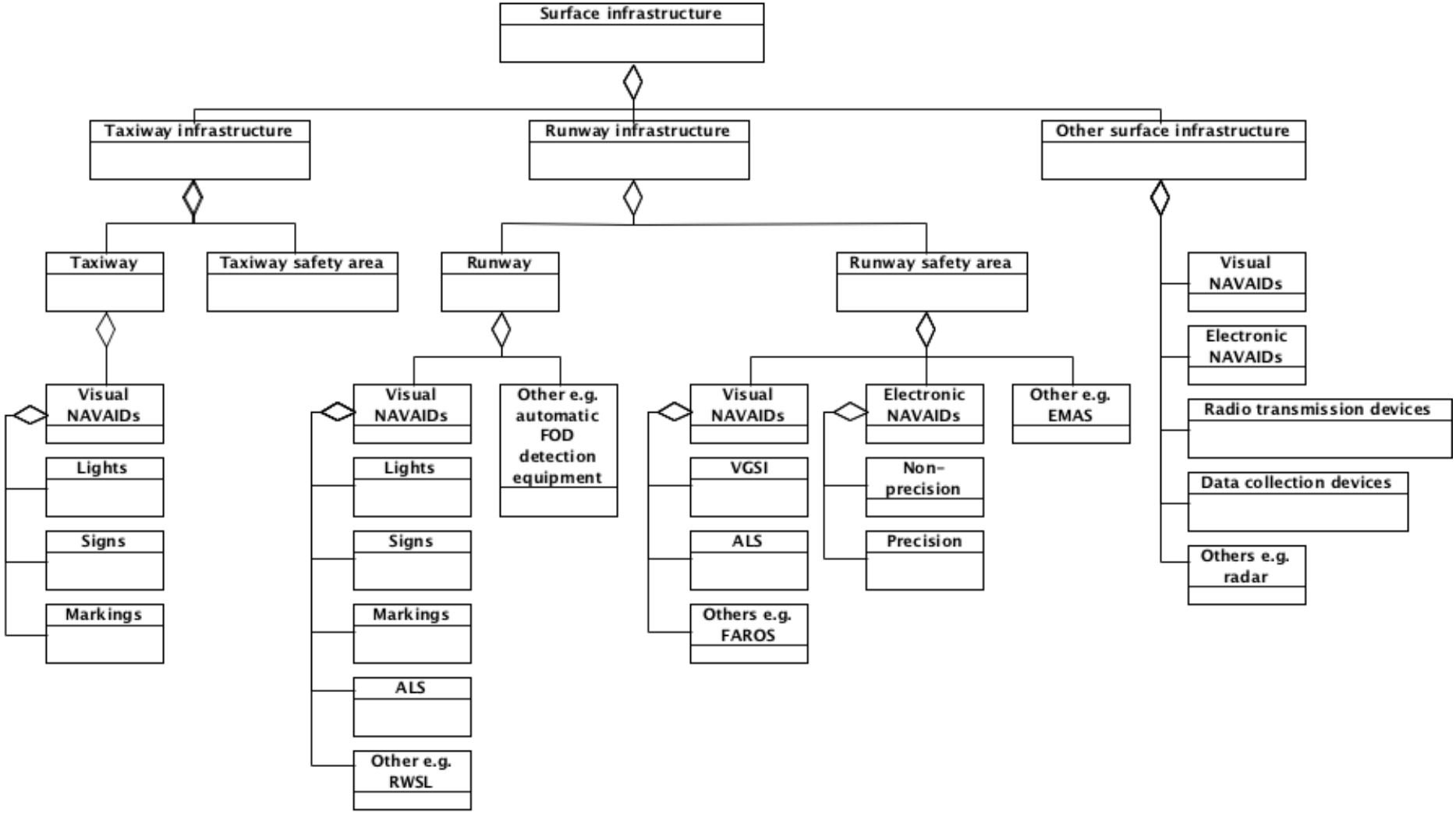


Figure 12: Airport surface infrastructure

To highlight possible differences in the surface infrastructure, the three case studies from Chapter 2 are extended following the same methodology as introduced in section 2.2.4. Using the airport surface infrastructure model shown in Figure 12 as a reference, Table 4 compares the surface infrastructure of LAX, LPL, and BOO.

Table 4: Case study – airport surface infrastructure

Surface infrastructure	**LAX**	**LPL**	**BOO**
Number of runways	4	1	1
Number of taxiways	51	6	12
Electronic NAVAIDs			
- Highest RWY category*	Precision Cat IIIa	Precision Cat II	Precision Cat I
Visual NAVAIDs			
- ALS configuration	Precision Cat IIIa	Precision Cat II	Precision Cat I
- RWY/TWY lights	According to regulatory requirements		
- RWY/TWY signs	According to regulatory requirements		
- RWY/TWY markings	According to regulatory requirements		
- Other	Runway Status Lights	-	-
Data collection devices (weather)	✓	✓	✓
Radio transmission devices	✓	✓	✓
Other surface infrastructure	Airport Surface Detection Equipment – Model X (ASDE-X)**	-	Overrun cable to stop military aircraft in case of an overshoot

* For airports with multiple runways the highest runway category is considered.
** ASDE-X is a safety tool that enables ATC to detect possible runway conflicts.

Table 4 highlights that the level of equipment and the complexity of the airport surface, in terms of runway and taxiway numbers, can vary significantly between airports.

3.2.3 Airport Authority Model

The airport authority's role is the management and maintenance of the airport surface, i.e. the provision of the infrastructure in a working condition. The airport authority's operations therefore include the inspection and maintenance of the manoeuvring area (e.g. foreign object debris (FO) inspections, runway / taxiway pavement maintenance) and the maintenance of the visual and electronic NAVAIDs. In addition, it is the airport operator's responsibility to close surfaces, for instance, during maintenance and construction periods. Construction management that includes the control of works and site management are also part of the authority's operations, as well as grass cutting, snow removal, wildlife control, and the initiation of preventive measures (e.g. spraying for bugs, wheat). In UML notation

the airport authority's tasks can be summarised using a package diagram as shown in Figure 13.

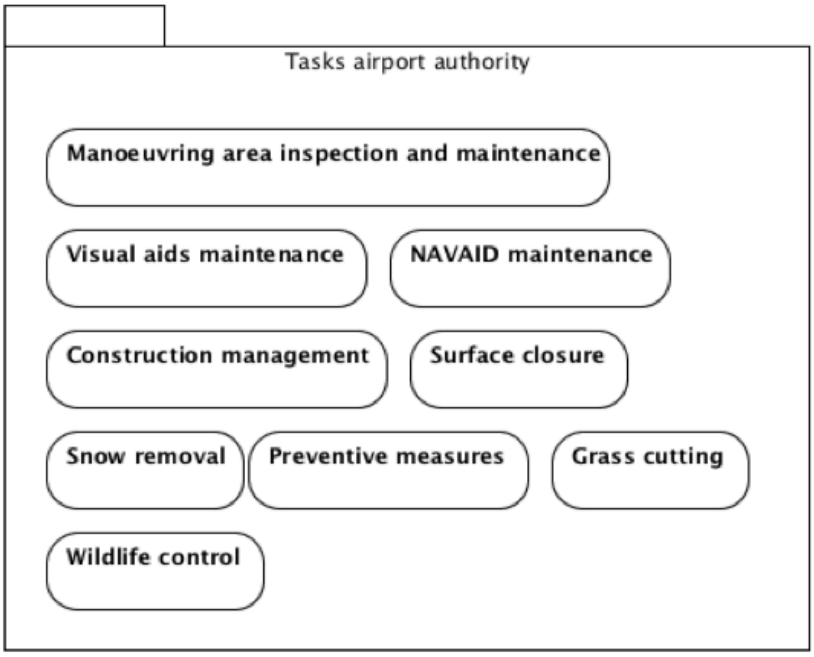


Figure 13: Tasks airport authority

Chapter 2 indicated that infrastructural components and activities may be sub-contracted. In such cases, the above listed tasks might fall to another stakeholder. For example, in Europe, electronic NAVAIDs are typically owned and maintained by the airport authority, whereas in the U.S. they are owned and maintained by the FAA, which is both, the ANSP and the regulatory body.

The airport authority operates on the manoeuvring area in the form of vehicles and / or pedestrians and the details on how V/PDs accomplish their tasks are described in section 3.2.5.

3.2.4 Pilot Model

The airport surface is used primarily for taxiing, landing and take-off. Incoming flights land on a runway and then use the runway and taxiway system to taxi to their assigned ramp at the apron, where ground handling (e.g. loading, refuelling, passenger boarding) takes place. Departure flights use the manoeuvring area to taxi from their ramp at the apron to an assigned runway for take-off.

3.2.4.1 High-level Task Analysis

The objective for a pilot's operation is the safe and efficient conduct of flights. A pilot's operation (flight operation) can be deconstructed into nine flight phases, as shown in Figure 14. These flight phases are derived from the ICAO's Accident / Incident Data Reporting (ADREP) system (International Civil Aviation Organization, 2006a).

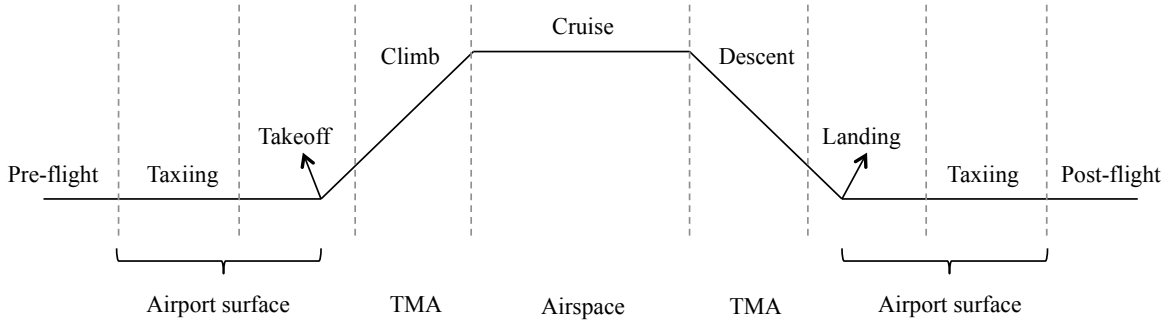


Figure 14: Flight phases

In the pre-flight phase the flight (i.e. pilots) and cabin crew board the aircraft with the intention to fly. The flight crew accepts the aircraft as airworthy and conducts the necessary pre-flight preparations. Subsequently, the aircraft is manoeuvred from the apron / ramp to its assigned runway, where it departs its origin and becomes airborne. The aircraft ascends in the Terminal Manoeuvring Area (TMA) until it reaches its flight level and then cruises en-route. Once the destination is reached, the aircraft leaves its flight level and starts its descent. After touchdown at its destination airport, the pilots manoeuvre the aircraft from the runway to its assigned ramp at the apron and carry out the necessary post-flight inspections, before leaving the aircraft. The corresponding UML notation is shown in Figure 15. The state diagram highlights the state of the aircraft during the different flight phases.

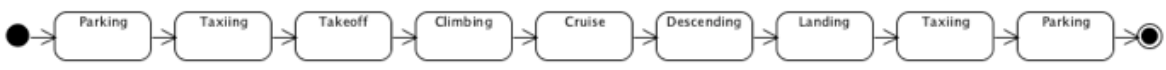


Figure 15: Aircraft state diagram

3.2.4.2 Hierarchical Task Analysis

The nine flight phases can be further deconstructed into tasks. To present the model of normal pilot operations in a more concise manner, only a high-level activity diagram is provided. Figure 16 indicates the tasks to be carried out in each phase of flight. In addition, spatial effects are shown, i.e. the location on the airport surface and the airspace, in which the tasks are carried out. Table 5 subsequently sets out a detailed outline of pilot operations, indicating the phase of flight and the tasks to be performed during each phase. In addition, the physical location of the aircraft during the flight operation, as well as spatial transition points (e.g. transition from taxiway to runway) are highlighted.

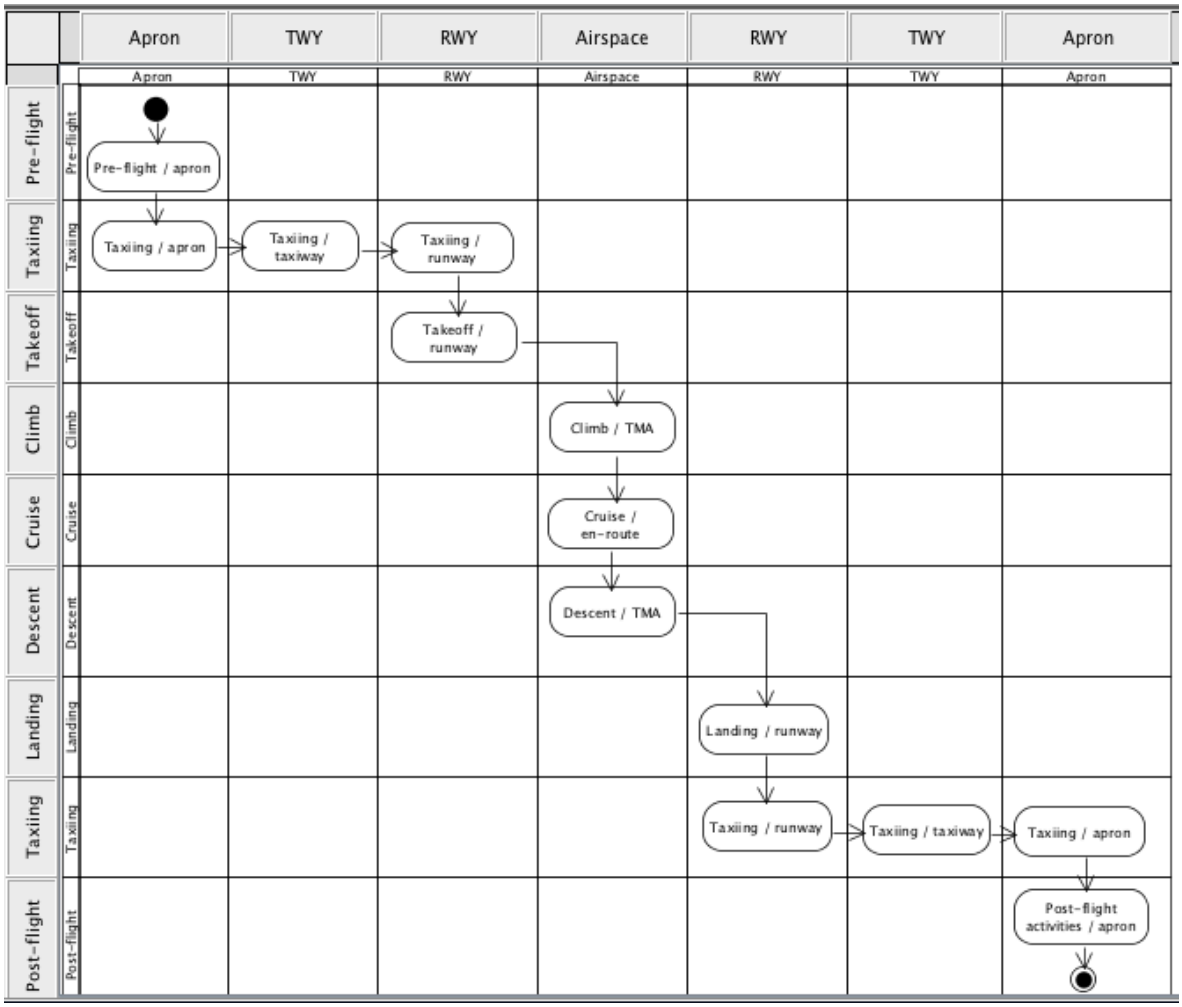


Figure 16: Outline activity model - pilot

Table 5: Task analysis – Pilot model

Flight phase	**Tasks to be performed**	**Spatial transition points**
Pre-flight	• Flight preparation (e.g. weather briefing, Notice to Airman (NOTAM) briefing (e.g. RWY / TWY closure), cabin crew briefing) • Check of aircraft maintenance records and acceptance of the aircraft as airworthy • Cockpit preparation (e.g. FMGS data insertion, calculations) • Exterior inspection (walk-around) • Take-off briefing (commander / first officer) • Weight and balance calculations • Before start checklist • Communication with ATC for clearance to push-back and start engine • Check area clear of obstacles and other traffic • Pushback • Engine start • After start checklist	Apron
Taxiing	• Communication with ATC for clearance to taxi and assignment of the next stopping point (can be an iterative process) • Check area clear of obstacles and other traffic (can be an iterative process) • Command aircraft movement (can be an iterative process) • Before take-off checklist • Monitor clearance from obstacles and other traffic* • Communication with ATC for clearance to enter the runway • Check area clear of obstacles and other traffic • Enter runway	Apron -> TWY TWY -> RWY
Take-off	• Communicate with ATC for clearance to take-off • Finish before take-off checklist	

	• Check area clear of obstacles and other traffic • Take-off • Monitor power margins and instruments, monitor speed increase, adjust flight profile accordingly* • Monitor clearance from obstacles and other traffic*	RWY -> TMA
Climb	• Communicate with ATC for climb profile instructions (can be an iterative process) • Adjust speed as required, monitor power margins (can be an iterative process) • Gear up • Flaps up • After take-off checklist (~1,000 – 1,500 ft.) • Decide when to turn on the autopilot (depending on personal preference from 400 ft. to 10,000 ft.) • Monitor flight profile execution as instructed, adjust flight profile accordingly* • Monitor clearance from obstacles and other traffic*	
Cruise	• Communicate with ATC for cruise flight profile instructions (can be an iterative process) • Adjust flight profile and instruments accordingly (e.g. altitude, speed, heading) (can be an iterative process) • Monitor clearance from obstacles and other traffic* • Cruise checklist or cruise briefing • Briefing (for approach / landing)	TMA -> en-route
Descent	• Communicate with ATC for clearance to initiate decent • Monitor flight profile execution as instructed, adjust flight profile accordingly* • Monitor clearance from obstacles and other traffic* • Approach checklist (~18,000 ft., ~10 min before landing) • Landing checklist (to be completed within the last 2,000 ft.) • Stable approach (for IFR 1,000 ft., for VFR 500 ft.) • Disable autopilot, assume manual control of the aircraft	En-route -> TMA
Landing	• Landing • Leave Runway • After landing actions • After landing checklist	TMA -> RWY RWY -> TWY

Taxiing	• Communicate with ATC for clearance to taxi and assignment of the next stopping point (can be an iterative process) • Check area clear of obstacles and other traffic (can be an iterative process) • Command aircraft movement (can be an iterative process) • Shut engines down (e.g. aircraft with 2 engines shuts one down) • Monitor clearance from obstacles and other traffic	TWY -> apron
Post-flight	• Parking • Engines – off • Parking checklist • Securing the aircraft checklist	Apron

* Monitoring is a permanent process.

3.2.4.3 Actors

Figure 17 defines the actors directly and indirectly involved in the safe and efficient conduction of flight.

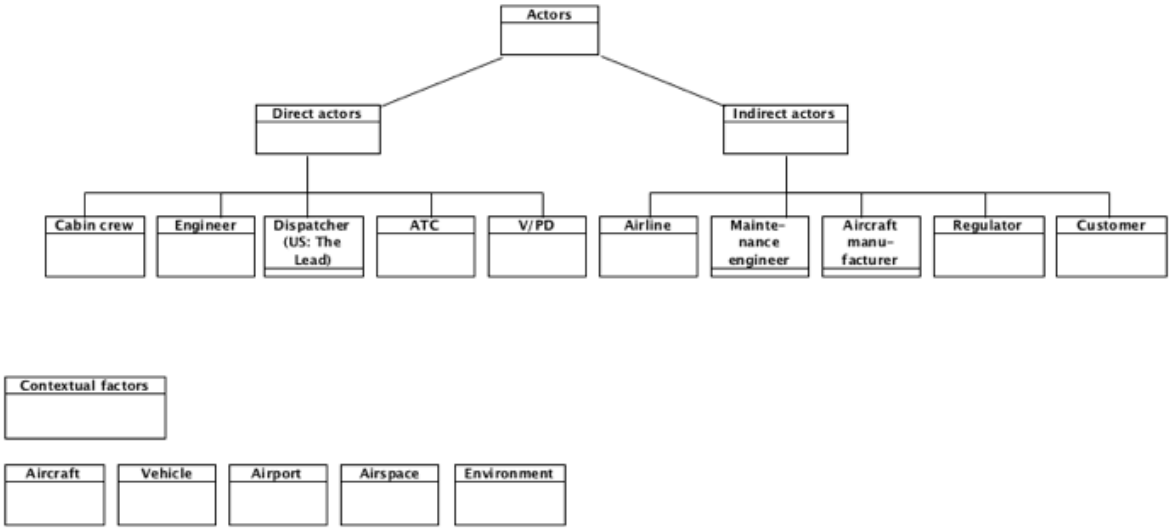


Figure 17: Actors in contact with pilots

The flight crew is in direct contact with the cabin crew, the engineer responsible for aircraft maintenance as well as the dispatcher responsible for loading and unloading the aircraft. The dispatcher is the connector between the aircraft / pilot and the ground handling personnel, as well as the gate agent (i.e. personnel responsible for boarding operations). In addition, the pilot is in contact with V/PD (e.g. V/PD personnel initiating the pushback).

3.2.5 Vehicle Driver / Pedestrian Model

Besides aircraft, V/PD also use the runway and taxiway system. The majority of vehicles and associated airport personnel, such as ground handling vehicles and equipment (e.g. fuel, catering, baggage), operate on the apron. Certain vehicles, however, are allowed to enter the manoeuvring area. These include tugs for towing aircraft, cars for runway condition checks, maintenance vehicles for, e.g., grass-cutting, vehicles involved in

construction work, or snow removal equipment in wintertime. In addition, pedestrians are also on the manoeuvring area, such as construction workers or maintenance personnel.

3.2.5.1 High-level Task Analysis

The overall objective of V/PDs is the safe and efficient conduction of a specific task. The operational phases are defined on a high level so as to fit the model to any V/PD operation on the manoeuvring area. V/PD operations can be summarised into five distinct phases: pre-task, taxi-out, task accomplishment, taxi-in, and post-task, which are outlined in Figure 18.

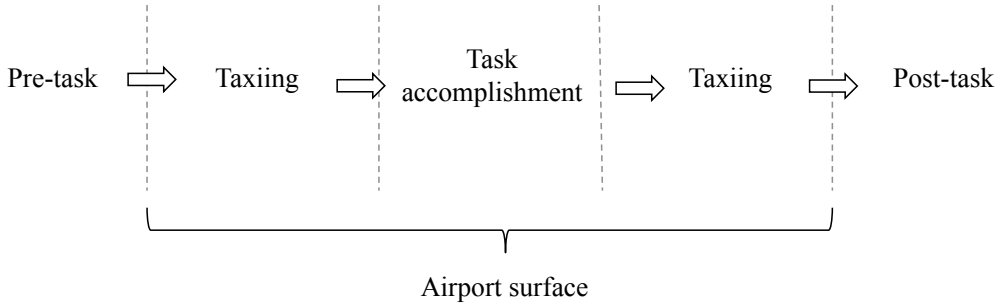
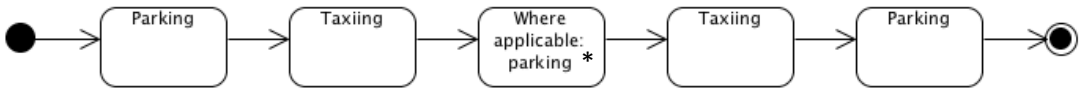


Figure 18: V/PD operational phases

The vehicle driver boards the vehicle with the intention to carry out a task. If applicable, he / she also carries out the necessary preparations for the operation, for instance, getting the snow removal equipment ready. Subsequently, the vehicle moves from its parking position (point A) to a point B on the airport surface, where it accomplishes its task (e.g. snow removal, runway inspection). Some task may require parking the vehicle on the manoeuvring, for instance, when the driver leaves the vehicle to inspect the infrastructure. Once the task has been carried out the driver manoeuvres the vehicle from point B back into its parking position. If required, post-operation tasks are carried out (e.g. getting the snow removal equipment ready for its next use), before the driver leaves the vehicle. The corresponding UML notation, shown in Figure 19, highlights the state of a vehicle during the different phases of operation.



* Specific tasks may require the parking of the vehicle during task accomplishment.

Figure 19: V/PD state diagram

3.2.5.2 Hierarchical Task Analysis

The five phases of V/PD operations may be further deconstructed. Figure 20 indicates the activities for each phase using a high-level activity diagram. Spatial effects are considered and a detailed outline of V/PD tasks is given subsequently in Table 6.

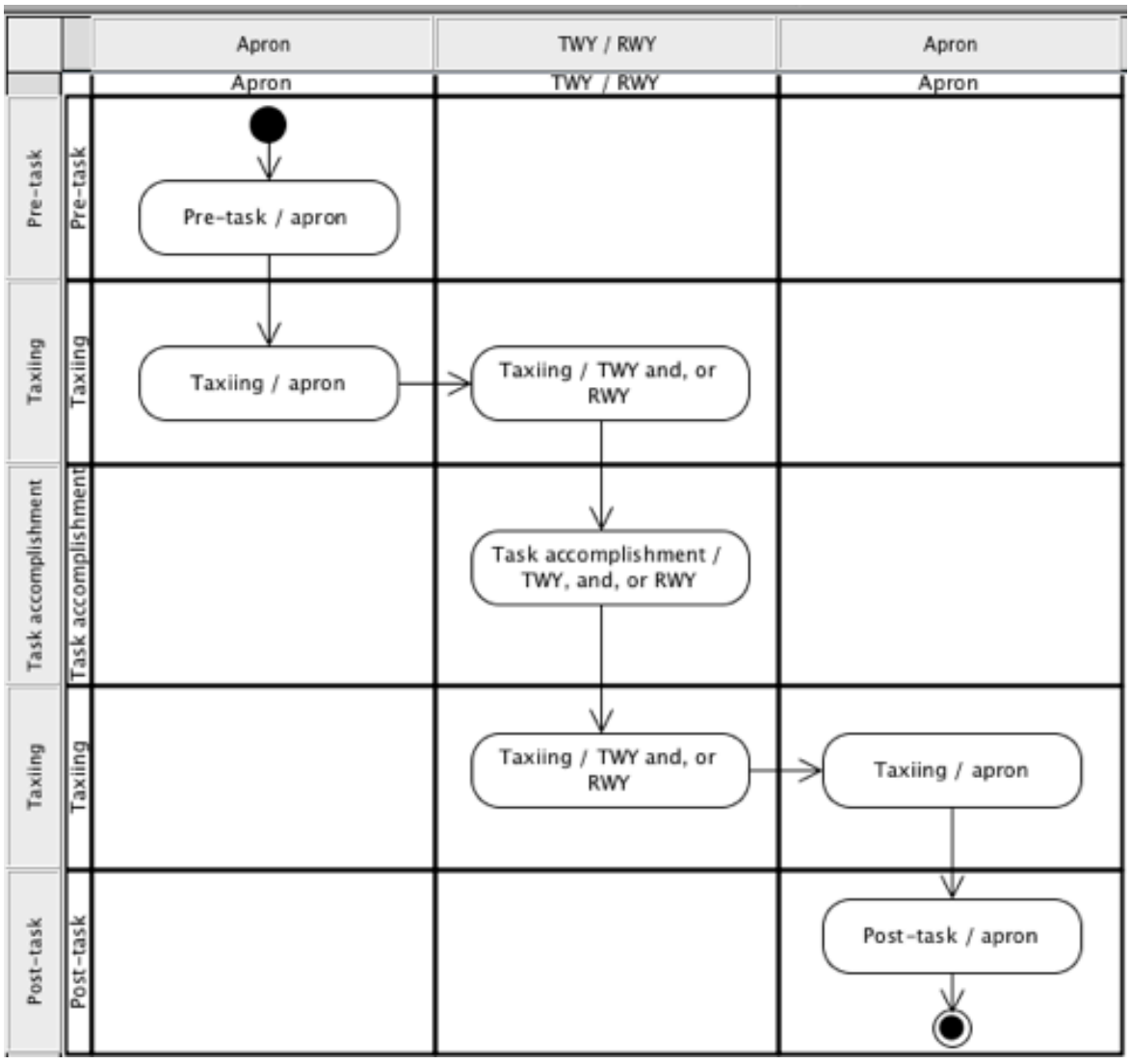


Figure 20: Outline activity model –V/PD

Table 6: Task analysis – V/PD model

Phase	**Tasks to be performed**	**Spatial transition points**
Pre-task	• If applicable, execution of necessary preparations for task accomplishment (e.g. get snow removal equipment ready) • Command surface movement on the apron • Communication with ATC to get clearance to enter the manoeuvring area • Command surface movement	Apron Apron -> TWY
Taxiing	• Communication with ATC for clearance to taxi and assignment of the next stopping point • Check area clear of obstacles and other traffic • Command surface movement • Monitor clearance from obstacles and other traffic* • Report clear once the requested runway / taxiway has been cleared [Taxi operations can be in iterative process]	(Depending on the tasks: a transition from TWY to RWY can take place)
Task accomplishment	• Accomplish task (e.g. runway inspection) • Communication with ATC for surface movement instructions necessary for task accomplishment and adjust movements accordingly • Monitor clearance from obstacles and other traffic [Communication with ATC (i.e. request for clearance, clearance confirmation, surface movement, report clear of runway / taxiway) can be an iterative process e.g. for each runway entry during the inspection]	
Taxiing	• Communication with ATC for clearance to taxi and assignment of the next stopping point • Check area clear of obstacles and other traffic • Command surface movement • Monitor clearance from obstacles and other traffic* [Taxi operations can be in iterative process] • Report clear of manoeuvring area	(Depending on the tasks: a transition from RWY to TWY can take place) TWY -> Apron

Post-task	• Parking • If applicable, execution of necessary post-task-processing	Apron

* Monitoring is a permanent process.

Note that there may be differences in operational practices between airports, depending on the underlying procedures. For instance, typically, a V/PD needs to contact ATC and ask for clearance to enter the manoeuvring area. Some airports, however, have 'free-range' procedures: in these circumstances V/PD are allowed to enter the manoeuvring area without contacting ATC for clearance, except to access an active runway. This reduces the amount of ATC communication.

3.2.5.3 Actors

Figure 21 provides an overview on the actors involved in V/PD surface operations.

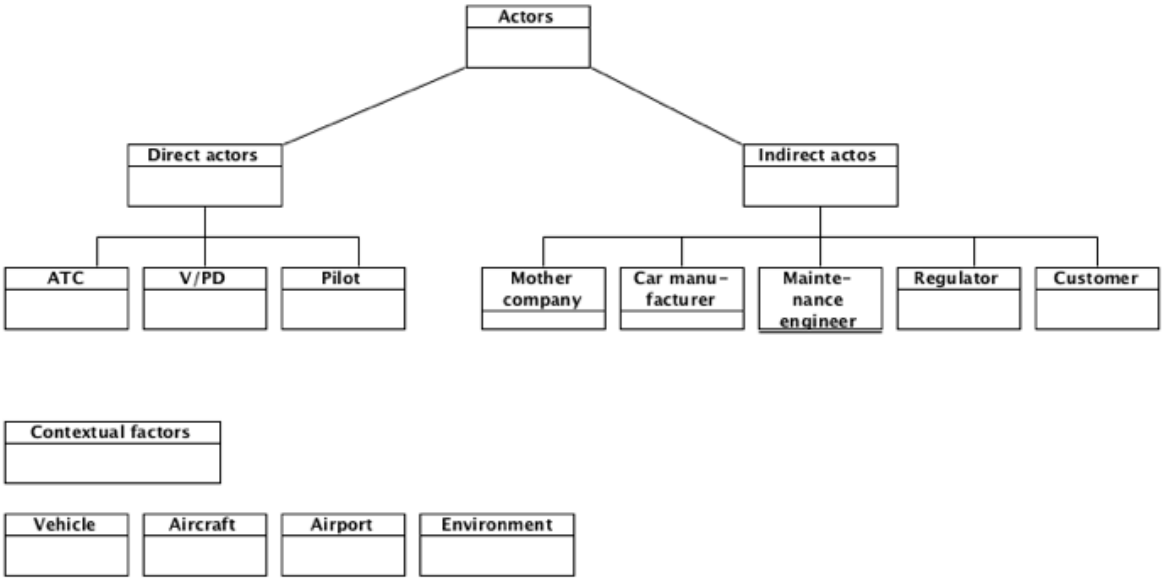


Figure 21: Actors in contact with V/PD

V/PD are in contact with ATC, pilots, and possibly also with other V/PD (e.g. if they work together).

The V/PD model has been developed on a high level, as it allows applicability of the model to all vehicle drivers and pedestrians that might be present on the airport surface. The following paragraph provides an overview on the various parties that are involved in ground handling. Ground handling takes place on the ramp / apron and is hence not within the scope of this research. Ground handling, however, illustrates very well the complexity of the airport system and the interactions of various stakeholders. Although ramp / apron

occurrences are not the subject of this research, all of the following V/PD's have the potential to compromise the safety of surface operations when infringing onto the manoeuvring area.

During ground handling the aircraft is in contact with the signalman for leading the aircraft into position and his / her co-workers for chocking and protecting the aircraft. In addition, an operator is needed for connecting the aircraft to the ground power unit (GPU), air conditioning unit (ACU), and air starter unit (ASU). Furthermore, there are the passenger boarding bridge, buses for passenger transportation, and medical staff for assisting disabled people to embark and disembark the aircraft. Luggage and cargo is transported to the aircraft using a tractor or carts and a conveyer belt allows access to the bulk hold. Operators then (un)load the aircraft. To (un)load pallets a loader can be used. In addition, there are catering vehicles and personnel, cabin servicing (i.e. cleaners), and a lavatory vehicle and potable water vehicle to prepare the aircraft for its next flight. A fuelling tanker as well as a tanker with anti-icing product for de-icing on the ramp are also part of the turn-around of an aircraft. If required, aircraft maintenance personnel is available to carry out first level repair and maintenance. Finally, a tug and potentially a tow bar, a tug driver, an operator for handling the tow bar, an operator for radio communications with the flight crew, and two operators to visualize the tips of the wings are needed for the pushback operations. As each of these ground handling operations can be carried out by a different service provider (i.e. company) there can be up to 40 operators in vehicles on the ramp servicing one aircraft at any given time.

Similarly, various vehicles, and operators with different tasks (e.g. airport operator, external stakeholders such as construction workers) may be present on the airport surface. Figure 22 summarises the actors involved in ground handling operations in a class diagram.

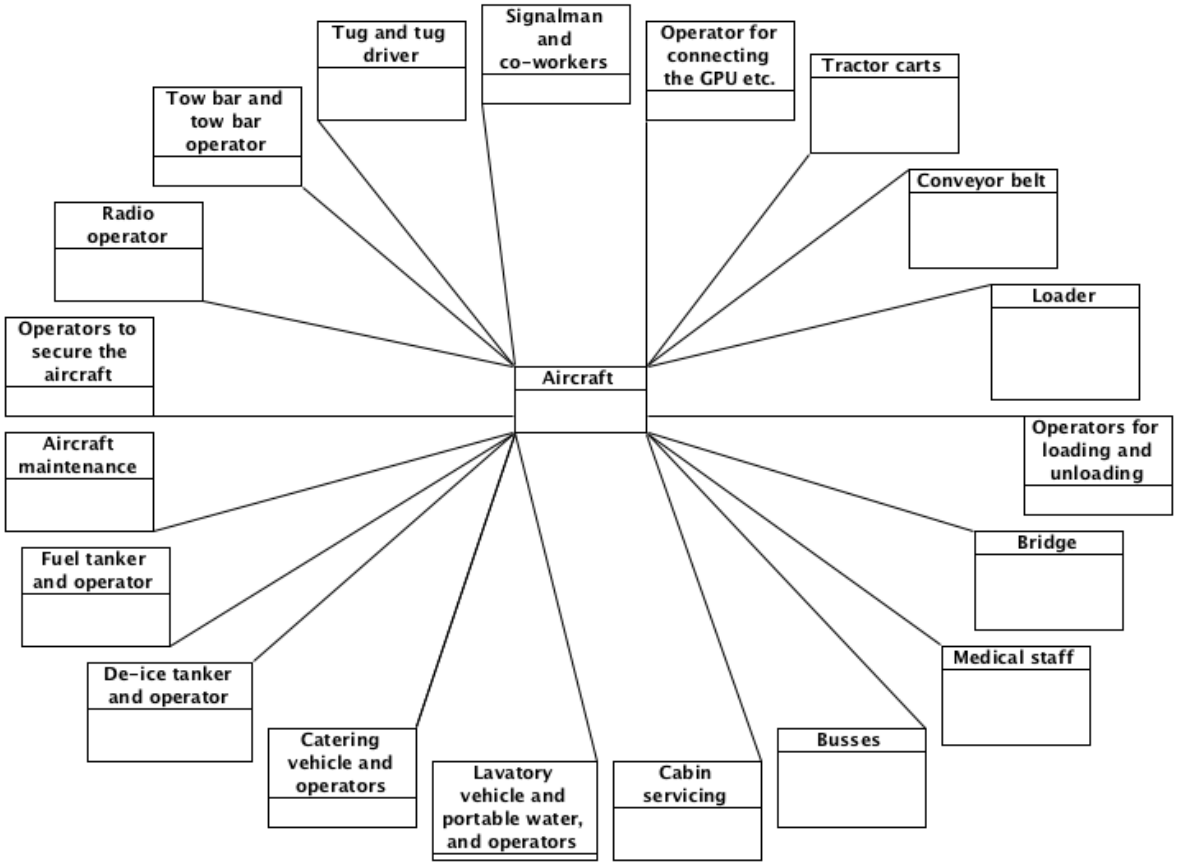


Figure 22: Ground handling actors

3.2.6 ATC Model

Besides pilots and V/PD, ATC plays a significant role in the safe flow of ground-movements. ATC provides three services: area control, approach control and the air traffic control tower, discussed in detail below.

- ***Area Control***

The Area Control Centre (ACC), as defined by the ICAO, or Air Route Traffic Control Center (ARTCC) as defined in the U.S. by the FAA, is responsible for the en-route phase of flight. The main function of controllers during this flight phase is the provision of separation between aircraft. To do so, controllers monitor the progress of flights and intervene when conflicts arise. In addition, they provide instructions, clearances and advice regarding flight conditions (Cook, 2007; International Civil Aviation Organization, 2001b; Subotic, 2007).

Typically, two controllers, a planning and a tactical controller, are in charge of each ATC sector. While they work as a team and are equally responsible for the safe, orderly and efficient handling of air traffic, they have clearly defined roles. The planning controller is responsible for the strategic planning of the traffic in a sector. He / she has to coordinate the entry and exit of flights into the sector, manage the flight progress strips, make flight data corrections in the Flight Data Processor (FDP), plan the traffic flow in such a manner as to minimise conflicts, and monitor emergency frequencies. The tactical controller is in direct contact with the aircraft. It is his / her role to communicate with the pilots, to accept aircraft into a sector, monitor their progress, and to detect and solve arising conflicts (Cook, 2007).

- ***Approach Control***

The Approach Control unit (APP), as defined by ICAO, or Terminal Radar Approach CONtrol (TRACON) as defined in the U.S. by the FAA is the ATC unit that provides services for the approach and departure phase. Its services extend from the runways until the aircraft is airborne or clear of the airport. Approach controllers are responsible for providing separation between aircraft in the climb and descent phase of flight (Cook, 2007; International Civil Aviation Organization, 2001b; Subotic, 2007).

- ***Aerodrome Control***

The Aerodrome Control Tower (TWR), as defined by ICAO, or Air Traffic Control Tower (ATCT) as defined in the U.S. by the FAA provides ATC services for the aerodrome, extending over runways, taxiways, aprons and airport stands. Its main responsibility is the management of the runways and the provision of a safe and efficient traffic flow on the ground. This includes aircraft as well as V/PD operating on the manoeuvring area. In addition, the TWR assists the Approach Control with take-offs and landings of aircraft and is responsible for circuit traffic. At busy airports in the U.S. the surface movement control or ground control provides supplementary services to aerodrome control. It provides ATC services for movements from the parking position to the departure end of the runway. In less busy airports, ground and aerodrome control are combined (Cook, 2007; International Civil Aviation Organization, 2001b; Subotic, 2007).

3.2.6.1 High-level Task Analysis

When mapping ATC's services to the flight phases introduced in section 3.2.4.1 seven ATC phases can be derived from the subject matter literature (e.g. Cook, 2007; International Civil Aviation Organization, 2001b; Subotic, 2007), as outlined in Figure 23.

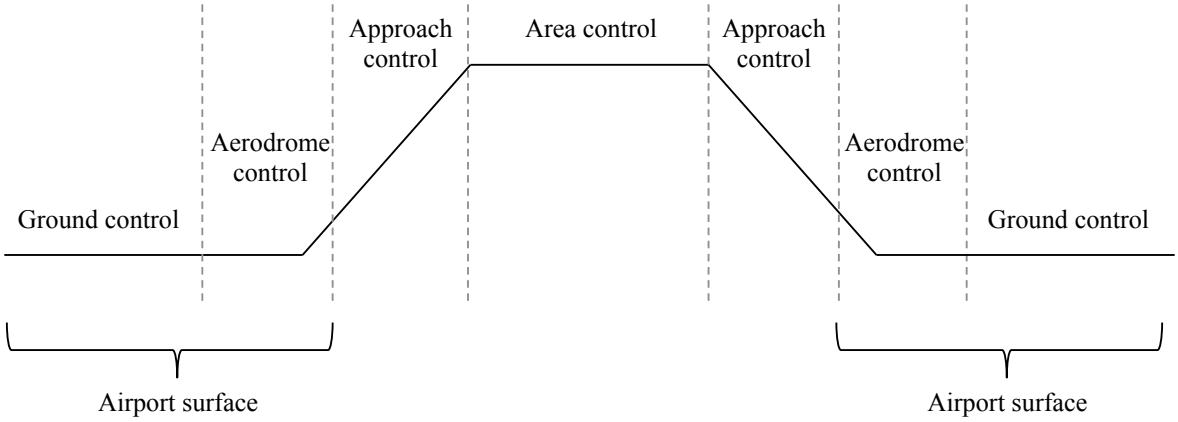


Figure 23: ATC operational phases

3.2.6.2 Hierarchical Task Analysis

Air traffic control operations are multi-tasking operations. A controller may handle multiple aircraft and / or vehicles simultaneously and, although tasks can be defined for ATC operations, no order can be assigned to them, since several tasks may be accomplished at the same time. For example, ATC can monitor ground movements, while communicating with a pilot using radiotelephony.

ATC tasks can be summarised using a package diagram (Figure 24). The tasks are the same for each ATC type (i.e. ground control, aerodrome control, approach control, area control).

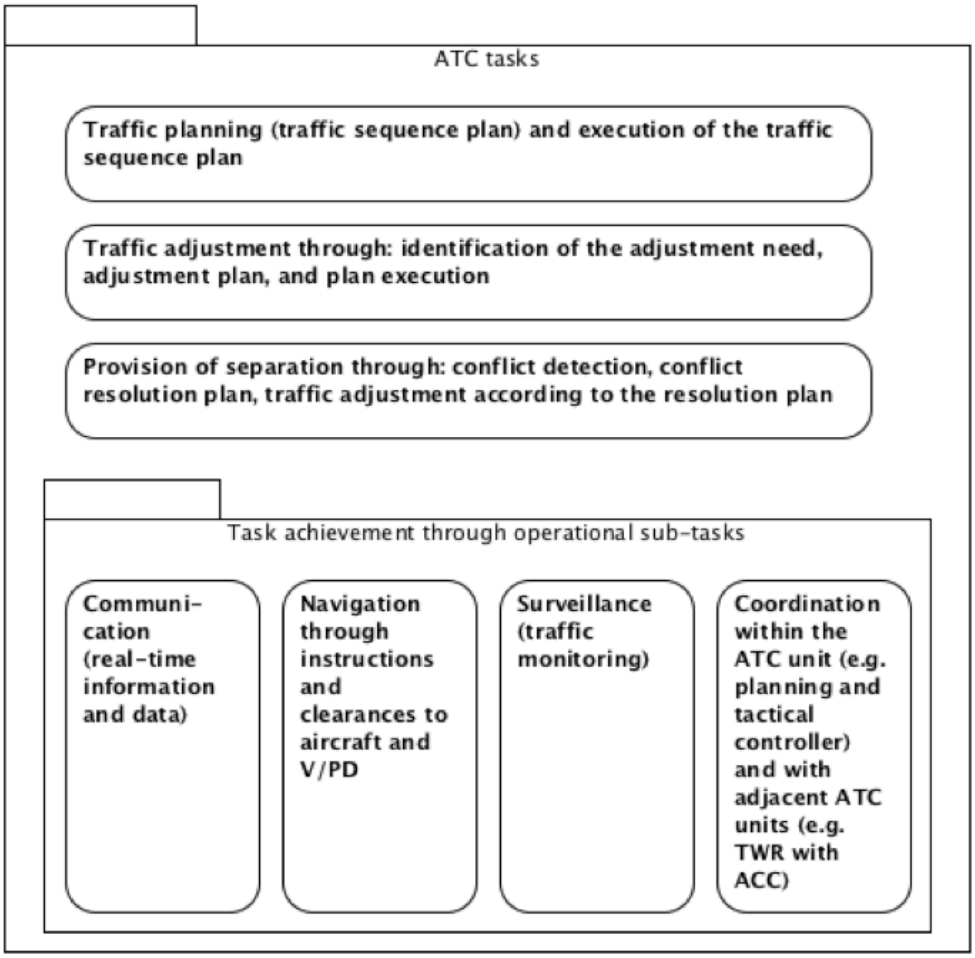


Figure 24: Normal ATC operations

When considering spatial effects, the controller itself does not change his / her physical location. It is the aircraft and the vehicles that change their state, i.e. physical location, as outlined in sections 3.2.4.2 and 3.2.5.2.

3.2.6.3 Actors

Figure 25 provides an overview on the actors involved in ATC operations.

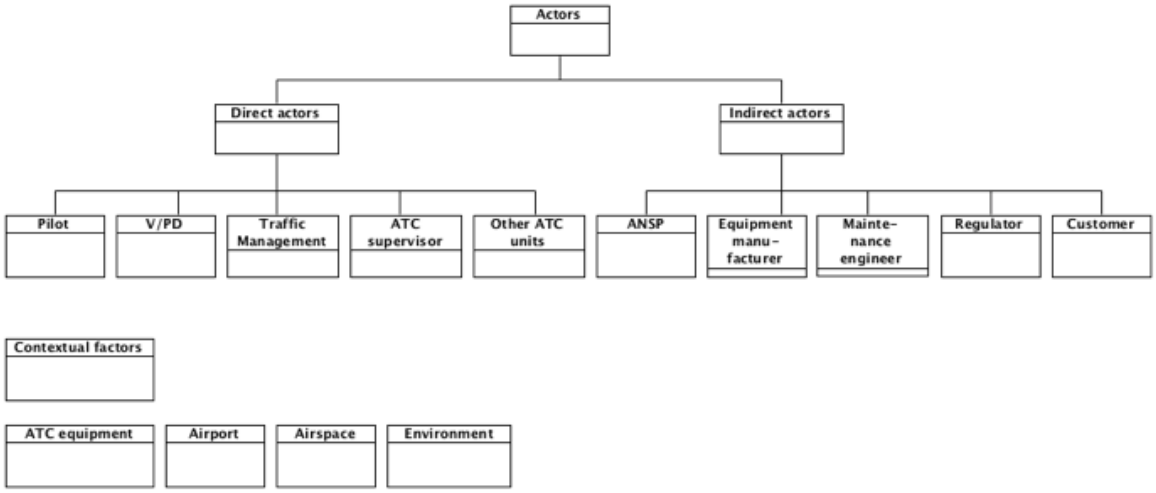


Figure 25: Actors ATC

3.2.7 Regulatory Model

The acceptable certification, licensing and operating procedures have to be developed and implemented by the regulatory body. The regulator also has to oversee that all stakeholders comply with the established regulations. The regulator's task was described in detail in Chapter 2 section 2.2.3.6 and can be summarised by the package diagram in Figure 26.

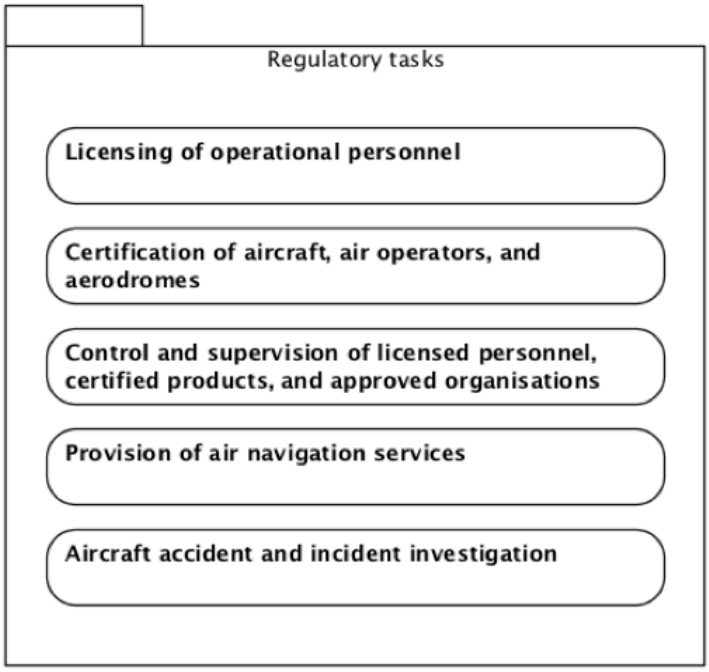


Figure 26: Tasks regulator

3.2.8 Interfaces

The previous sections have introduced the operations and tasks for each of the main actors in isolation. In reality though the stakeholders interact. The interface between the three stakeholders that interact directly on the airport surface (i.e. pilot, ATC, V/PD) is communication (i.e. information and data) as shown in Figure 27.

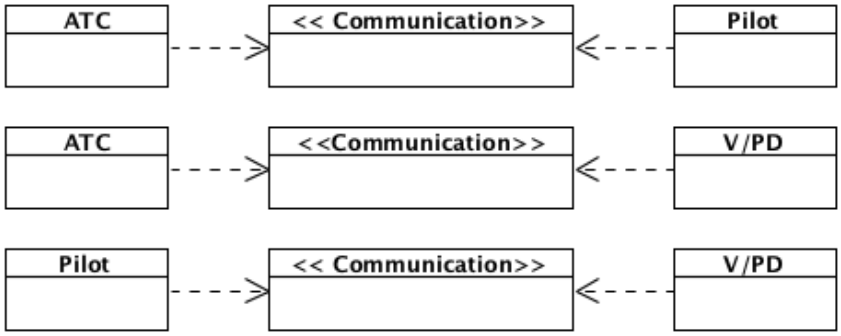


Figure 27: Interfaces

3.2.9 The Airport Surface System

Based on the models developed for each of the aviation stakeholders and their interfaces (section 3.2.2 - 3.2.8) the *airport surface system* can be derived. The airport surface system comprises various components. Firstly, the aircraft operators, i.e. the flight (pilots) and cabin crews that work for an airline and follow the airline's procedures and regulations. Secondly, the vehicle operators and pedestrians (V/PD) who are employed by an operating company, for instance ground handling company, and follow the procedures and regulations set by this company. Third, the system comprises air traffic service providers that are controllers who work for an ANSP and follow the ANSPs procedures and regulations. The technical infrastructure to support flight, V/PD and ATC operations are the aircraft, vehicles and ATC equipment. Aircraft manufacturers, car manufacturers and original equipment manufacturers (OEM) provide this infrastructure and maintenance engineers ensure that it is maintained in a working condition. In addition, the airport surface system comprises ATM, the airport and airspace, the natural environment, external stakeholders, customers, and the regulatory system. Figure 28 illustrates the airport surface system architecture and the interactions between its stakeholders and components in summary.

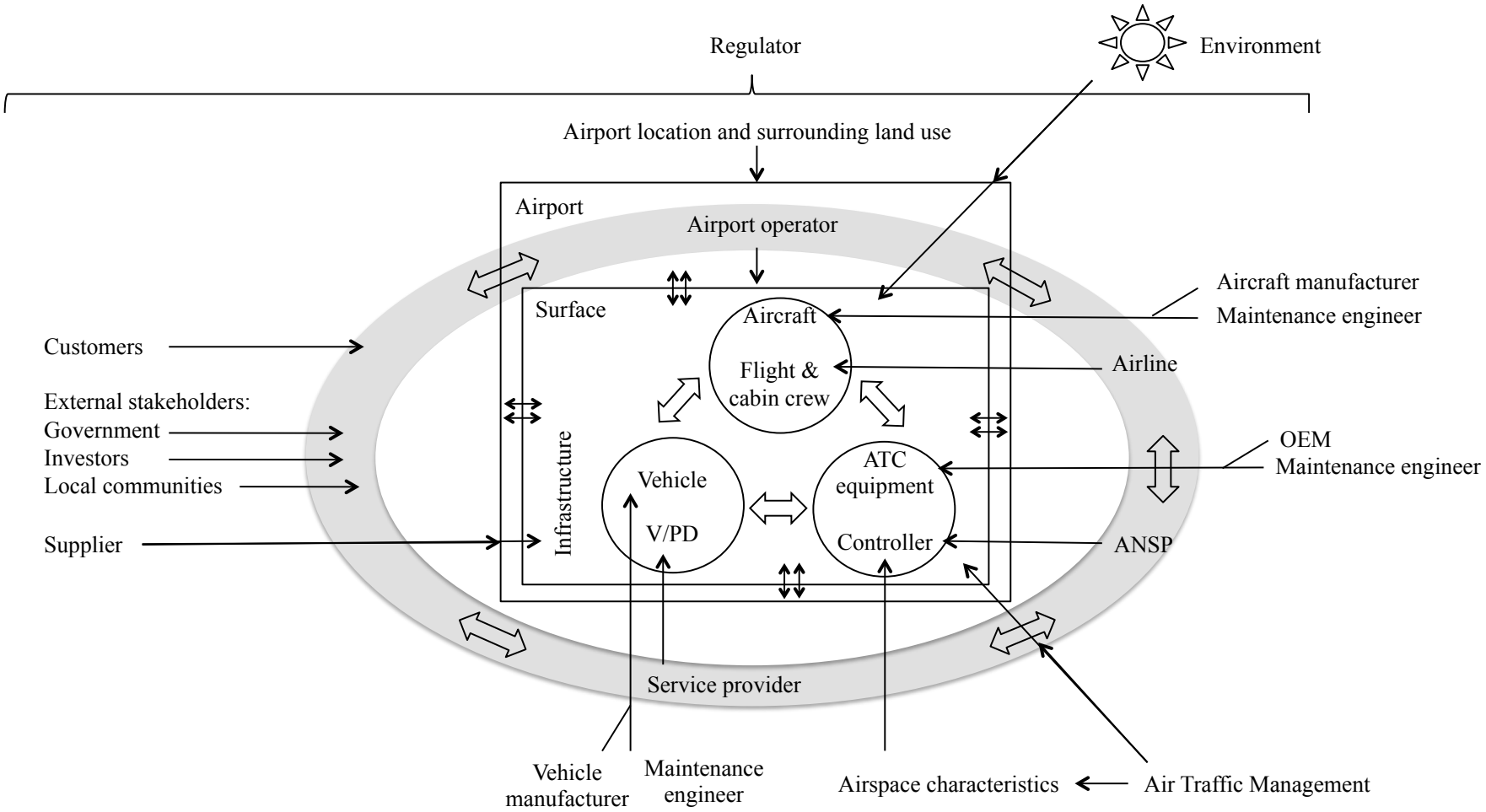


Figure 28: Airport surface system architecture

Figure 28, illustrates that three operators (i.e. pilots, V/PD, ATC) interact directly with each other on the airport surface. The airport authority is responsible for the provision of the infrastructure in working conditions. The corresponding service providers (airport operator, airline, ANSP, V/PD service provider) influence the surface operations directly, for instance through procedures. In addition, there is an interface (double arrows ⇄) between the airport surface and its surrounding infrastructure (apron) and the operations on both sides of the line that separates the manoeuvring area from the apron influence each other (e.g. pilot operations start at the apron and transfer to the manoeuvring area during taxi). The service providers also interact with one another, for example, to negotiate contractual arrangements for service provision between handling companies and airlines. In addition, the service providers are influenced by the customers (e.g. customer demand influences the services that are offered) and other external stakeholders (e.g. noise complaints / negotiations between local communities and airport operators). However, customers and external stakeholders do not have a direct influence on airport surface operations. Finally, the regulator oversees the whole system in order to ensure the provision of safe and efficient operations.

3.3 Time Effects

After having developed a process model of normal airport surface operations, this section analyses the impact of time on the operations, i.e. how different events in time, or characteristics of time, affect the operations and or tasks (operations / tasks). For instance, a flight cancellation (i.e. event in time) makes the operation of a pilot, i.e. flying from point A to point B, unneeded. Similar, it needs to be analysed whether the process model applies to different time periods (i.e. characteristics of time), such as peak vs. non-peak operations, or daytime vs. nighttime operations. The aim is to identify the time variant and invariant elements in the operations / tasks of the stakeholders.

This analysis focuses on external influences, i.e. events in time, or characteristics of time, that can influence the operations / tasks. The consequences of failures within the process (e.g. incorrect cockpit preparation due to human error) are considered in Chapters 5 to 9.

3.3.1 Methodology

To begin with, a list of criteria that define the characteristics of operations and tasks was developed (e.g. start time, duration, end time). Afterwards, the airport surface system in section 3.2.9, Figure 28, was used to define a time effect to be used for this analysis. As introduced above, this analysis focused on the impact of external influences. When analysing the airport surface system one significant external factor, i.e. the airport environment, and in particular the weather, became apparent. Weather is an external environmental factor that impacts on all airport surface operations and associated actors in a manner that is random and cannot be influenced.

The impact of weather on the process model was subsequently assessed, i.e. it was systematically assessed how this time effect impacts on each of the criteria that define the operations and tasks of the stakeholders. Based upon this, it was determined whether these criteria are time variant or invariant. The analysis focused on the actors directly involved in airport surface operations and considered pilot, V/PD and ATC operations. In the case of V/PD operations, two scenarios were chosen. First, the impact of time effects on the operations / tasks of the airport authority were analysed and, second, the influence of time effects on ground handling was assessed. The scenarios were chosen as these two parties operate daily on the airport surface. Other V/PD, such as construction vehicles, were excluded since they only operate on the manoeuvring area when needed. To verify the results, other time effects (e.g. demand changes, delay) were derived from the KPIs and drivers (see Chapter 2 section 2.4.1) and their impact systematically assessed.

To identify system effects, interactions between the operations / tasks of different actors were analysed in a final step. The analysis focused on direct interactions, i.e. parties that are in direct contact with each other during an operation. The definition of direct actors in contact with pilots, V/PD and ATC, respectively (sections 3.2.4.3, 3.2.5.3, 3.2.6.3) helped to identify the following six scenarios:

- Impact of pilot operations on ATC operations / tasks
- Impact of pilot operations on V/PD operations / tasks (case ground handling)
- Impact of V/PD operations on pilot operations / tasks (case ground handling)
- Impact of V/PD operations on ATC operations / tasks (case airport authority)
- Impact of ATC operations on pilot operations / tasks
- Impact of ATC operations on V/PD operations / tasks (case airport authority).

The results were validated with the following SMEs following the methodology described in section 3.1.3:

- Airfield Operations Shift Supervisor of a U.S. airport operator,
- FAA Line Manager / Tower Supervisor, and
- Chief Pilot of a U.S.-based airline.

3.3.2 Results

Ten criteria were identified in relation to operations / tasks that can be influenced by time effects:

- Subject of the operation, i.e. the ability of time effects to change the subject of normal operations as defined in the process model (e.g. requirement of a new operation to accommodate time effects);
- Seasonal requirements of an operation, i.e. operations are only required during specific time periods (e.g. winter operations);
- Occurrence of an operation, i.e. whether an operation takes place or not;
- Scheduled start, and / or end time of operations;
- Operation processing time, i.e. the period of time that is needed to complete an operation;
- Frequency of operations, i.e. how many times an operation takes place;
- Subject of the tasks, i.e. the ability of time effects to change the tasks that are necessary to complete an operation as defined in the process model (e.g. new tasks needed)
- Task sequence, i.e. the sequence in which tasks are to be completed;
- Occurrence of individual tasks, i.e. whether all tasks are carried out during the operation;
- Frequencies of tasks, i.e. how many times the individual tasks are carried out.

Table 7 summarises time variant and time invariant factors in relation to these ten criteria for pilots, V/PD and ATC.

Table 7: Time variant and invariant operations and tasks

Impact of time effects on	Pilot	V/PD (Airport authority)	V/PD (Ground handling)	ATC
Operations				
Subject of the operation	Invariant	Variant	Invariant	Invariant
Seasonal requirement of an operation	Invariant	Variant	Variant	Invariant
Occurrence	Variant	Variant	Variant	Variant
Scheduled start, and, or end time	Variant	Variant	Variant	Variant
Operation processing time	Variant	Variant	Variant	Variant
Frequency of operations	Variant	Variant	Variant	Variant
Tasks				
Subject of the tasks	Invariant	Variant	Invariant	Invariant
Task sequence	Invariant	Variant	Invariant	Variant
Occurrence	Variant	Variant	Variant	Variant
Frequencies of tasks	Variant	-	-	Variant

Variant: Time effects can influence this factor.
Invariant: Time effects cannot influence this factor.
-: Process model is not detailed enough to draw conclusions (i.e. detailed models of each V/PD task would be required).

3.3.2.1 Pilot Model

The subject of a pilot's operation is the safe and efficient conduct of flights, i.e. flying an aircraft from point A to point B and time effects cannot change this. In addition, this operation is an all the year round operation and not dependent on the season. The job of a pilot is, therefore, always flying an aircraft. Time effects can influence the occurrence of the operation, e.g., weather-related problems can lead to flight cancellations. In this case the whole operation is cancelled. Other reasons for flight cancellations include strikes and the expiry of the flight crew duty time caused by prior delays.

External factors can not only compromise the entire operation, but also impact on its scheduled start and end time. For example, flight delays caused by severe weather may delay an operation. Similarly, the operation processing time can vary: flights might be ahead of schedule (e.g. through preferential wind conditions), or delayed (e.g. severe weather causes holding of aircraft in the air or diversions from the anticipated route). The latter case might lead to safety compromising situations when, for instance, delays at congested airports lead to flight crews feeling pressured not to lose their slots (Airbus, 2004c).

Moreover, the frequency of operations is time variant. For instance, bad weather causes an aircraft to divert to land at a destination other than that scheduled. In this case, the pilot has in fact flown the aircraft from point A to point C and, as a result, the aircraft is in the wrong position and an additional operation is needed to fly the aircraft to point B.

Considering the tasks of a pilot, the tasks and their sequence are invariant and do not change. The occurrence of the individual tasks is dependent on the occurrence of the operation, i.e. when the operation takes place all tasks will take place as well. If an operation is cancelled no tasks are carried out. The frequencies of individual tasks can increase, however. For instance, holding an aircraft in the air, or diverting its route due to bad weather, will lead to an increased communication with ATC and an increased amount of times instruments in the cockpit need to be adjusted. It is important to point out that the frequencies of tasks can only increase. When an operation takes place, all tasks must be carried out since any omission would compromise safety.

3.3.2.2 Vehicle Driver / Pedestrian Model – Airport Authority

Section 3.2.3 defined the operations of the airport authority. To recap, it is the airport authority's responsibility to provide the infrastructure in working conditions, including operations such as manoeuvring area inspection and maintenance, surface closures, and wildlife control. These operations are time variant, i.e. new operations may be needed. For example, in a circumstance where a diverted aircraft lands at an airport where it was not expected it can be the airport authority's responsibility to coordinate the servicing and future operations for that aircraft. In addition, the operations of the airport authority are highly influenced by seasonal requirements (e.g. snow removal, grass cutting). Just as for pilots, the occurrence of an operation, its scheduled start and end time, as well as the operation processing time, are time variant and can be influenced by various factors (e.g. bad weather, peak times, traffic volume to be handled). Also, the frequency of operations can increase due to time effects. For instance, every airport has a minimum requirement for how many runway condition checks need to be carried out per day (e.g. once per shift / every eight hours) but sometimes more checks might be necessary (e.g. wind blew debris on the manoeuvring area).

The process model for V/PD was developed on a high-level so as to accommodate all kinds of vehicle drivers, pedestrians, and their operations. Thus, if new operations and

tasks become necessary the process model will still fit. This high-level modelling, however, does not allow for a detailed analysis of the frequencies of individual tasks, although it can be assumed that only an increase in frequency is possible, since any omission of tasks will always lead to situations that compromise safety.

3.3.2.3 Vehicle Driver / Pedestrian Model – Ground Handling

The findings for the operations / tasks of ground handling are identical to those for the airport authority, with one exception. It was shown that in some cases time effects could create new operations and tasks for the airport authority. This is not true for the individual parties involved in ground handling. For instance, the operation of a fuel tanker and its operator will always be fuelling the aircraft.

3.3.2.4 ATC Model

The operations of ATC, i.e. controlling the traffic, are time invariant: traffic control is not in itself dependent on seasonal effects. However, there are events in time (e.g. ATC strike) that can make ATC operations redundant. The time taken to process an aircraft, as well as the start and end time of the operation, are more flexible than the operations of pilots and V/PD, and are dependent on the current traffic situation. Hence, the operations are time variant. Also, the frequency of operations is flexible since new aircraft can enter a sector (e.g. through re-routing due to bad weather) and create more workload for ATC.

If ATC operations take place, their tasks are invariant. In contrast to pilots and V/PD (ground handling), however, the task sequence can change because air traffic control is a multi-task job. The frequency of individual tasks can also increase depending on the traffic situation.

3.3.2.5 Duration of Time Effects

The high-level architecture of time effects developed here illustrates whether or not an impact on surface operations exists. This impact can vary in its duration. For instance, a local thunderstorm might disrupt the operations for an interval of an hour, whereas a strike might disturb the operations for several days. In extreme cases, e.g. after an earthquake the

operations may not resume for several months. Nonetheless, the high-level architecture remains true independent of the time interval.

3.3.2.6 System Effects

After having analysed the impact of time effects on the operations of individual actors, system effects were analysed. Tables 8 to 10 show the results. The tables aim to highlight whether the operations / tasks of one party can impact the operations / tasks of another party in direct contact. Note that the effect does not necessarily have to affect the same criteria (e.g. the increase of actor A's task frequency can influence the start time of actor B's operation). Thus, Tables 8 to 10 highlight for each criteria only whether a system effect exists or not. Grey shaded cells represent time variant criteria.

Table 8: System effects pilot model

V/PD (Ground handling)		**Pilot**		**ATC**
		Operations		
No effect		Subject of the operation		No effect
No effect		Seasonal requirement of an operation		No effect
Effect (e.g. no handling needed)	←	Occurrence of operations	→	Effect (e.g. no ATC control needed)
Effect (e.g. on start, end, processing time of operations)	←	Scheduled start, and, or end time	→	Effect (e.g. on start, end, processing time of operations)
Effect (e.g. on start, end, processing time of operations)	←	Operation processing time	→	Effect (e.g. on start, end, processing time of operations)
Effect (e.g. more V/PD operations needed)	←	Frequency of operations	→	Effect (e.g. more ATC operations needed)
		Tasks		
No effect		Subject of the tasks		No effect
No effect		Tasks sequence		No effect
Effect (e.g. no handling needed)	←	Occurrence of tasks	→	Effect (e.g. no ATC control needed)
Effect (e.g. on start, end, processing time of operations)	←	Frequencies of tasks	→	Effect (e.g. on frequency of ATC tasks, e.g. communication)

Table 9: System effects airport authority model

ATC*		V/PD		Pilot**
		Operations		
Effect (e.g. on frequency of ATC tasks e.g. communication)	←	Subject of the operation	→	Effect (e.g. on frequency of pilot tasks e.g. communication)
Effect (e.g. on frequency of ATC operations)	←	Seasonal requirement of an operation	→	Effect (e.g. on happening/occurrence of operations)
Effect (e.g. no ATC control needed)	←	Occurrence of operations	→	Effect (e.g. no flight possible)
Effect (e.g. on start, end, processing time of operations)	←	Scheduled start, and, or end time	→	Effect (e.g. on start, end, processing time of operations)
Effect (e.g. on start, end, processing time of operations)	←	Operation processing time	→	Effect (e.g. on start, end, processing time of operations)
Effect (e.g. on frequency of ATC operations)	←	Frequency of operations	→	Effect (e.g. on start, end, processing time of operations)
		Tasks		
Effect (e.g. on frequency of ATC tasks e.g. communication)	←	Subject of the tasks	→	Effect (e.g. on frequency of pilot tasks e.g. communication)
Effect (e.g. on frequency of ATC tasks e.g. communication)	←	Tasks sequence	→	Effect (e.g. on frequency of pilot tasks e.g. communication)
Effect (e.g. no ATC control needed)	←	Occurrence of tasks	→	Effect (e.g. no flight possible)

* V/PD impact on ATC mainly if they operate in form of the airport authority.
** V/PD impact on pilots mainly if they operate as ground handling V/PD.

As set out above, the influence of V/PD is analysed using two case studies, airport authority and ground handling. The model of direct actors showed that airport authority V/PD are in direct contact with ATC (e.g. ATC clearance is required for V/PD operations on the manoeuvring area), whereas ground handling is directly linked to the aircraft and its associated operations (e.g. ground handling operators provide the servicing for aircraft).

For example, in a situation where the subject of operations for V/PD has changed due to an incoming diverted aircraft, the airport authority is required to take over a coordinating role. This new operational role and its associated tasks can influence both ATC and the pilot, since it increases specific tasks (e.g. communication). Similarly, seasonal requirements influence the direct links. Snow removal operations increase ATC's operations and aircraft de-icing is a prerequisite for flight operations. The occurrence of V/PD operations influences the occurrence of ATC and flight operations (e.g. if the airport authority strikes, the infrastructure cannot be maintained in a working condition and hence the conduct of flights might not be safe). The start, end, and processing times of V/PD

operations directly influence the start, end, and processing times of ATC and pilot operations. If no V/PD tasks take place, the operations of ATC and pilots cannot take place as well (e.g. unserviced aircraft cannot fly and hence no air traffic control is needed).

Table 10: System effects ATC model

Pilot		ATC		V/PD (Airport authority)
Operations				
No effect		Subject of the operation		No effect
No effect		Seasonal requirement of an operation		No effect
Effect (e.g. no flights possible)	←	Occurrence of operations	→	Effect (e.g. no V/PD operations possible)
Effect (e.g. on start, end, processing time of operations)	←	Scheduled start, and, or end time	→	Effect (e.g. on start, end, processing time of operations)
Effect (e.g. on start, end, processing time of operations)	←	Operation processing time	→	Effect (e.g. on start, end, processing time of operations)
Effect (e.g. on start, end, processing time of operations)	←	Frequency of operations	→	Effect (e.g. on start, end, processing time of operations)
Tasks				
No effect		Subject of the tasks		No effect
Effect (e.g. on start, end, processing time of operations)	←	Tasks sequence	→	Effect (e.g. on start, end, processing time of operations)
Effect (e.g. no flights possible)	←	Occurrence of tasks	→	Effect (e.g. no V/PD operations possible)
Effect (e.g. on start, end, processing time of operations)	←	Frequencies of tasks	→	Effect (e.g. on frequency of ATC tasks, e.g. communication)

In summary, system effects were found for direct actors. It was identified that the operations / tasks of one actor do not need to influence the same criteria of another actor. Indeed, often, other criteria are affected (e.g. actor A's task frequency can influence the start time of actor B's operation) and multiple effects can be induced (e.g. a delayed end time of actor A's operation influences the start time of actor B's operation and, potentially, its processing time since the disruption to the schedule may occasion additional tasks to accommodate the new timings).

Effects do not only occur between direct actors: in fact, an action of one actor can affect the whole system. For example, although ground handling personnel are not in direct contact with ATC they can impact on air traffic control indirectly, e.g. if no ground

handling takes place the aircraft cannot fly, which in turn means that ATC does not need to control that aircraft. Often, a time effect can start a chain of events involving all relevant actors at an airport.

Furthermore, it was identified that only time variant factors influence another party's operations / tasks.

3.4 Summary

This chapter has contributed to the second research objective by developing an initial process model of normal airport surface operations. Individual models were developed to represent the activities of, and define the interfaces between the five main stakeholders (airport authority, pilot, V/PD, ATC, regulator). A state-of-the-art high-level integrated architecture of the airport surface system was then derived from these individual models. This is the first such model of airport surface operations to represent the interactions of all relevant stakeholders and the physical airport infrastructure. In addition, spatial and temporal effects were highlighted. A profound understanding of surface operations is necessary before the safety of the system can be analysed and, therefore, the developed system architecture serves as an initial reference model to guide the development of airport SMS.

The main characteristics of airport surface operations, as identified in this chapter, are: complexity, multiple actors, interactions and dependencies, and dynamics. In addition, it was indicated that there are factors that can compromise the safety of the system and that the assumption of 'normality' may not always be fulfilled in reality. To manage such situations, organisations, including airports, are required to implement Safety Management Systems (SMS). Therefore, the next chapter introduces the concept of safety and SMS in detail.

4 Airport Safety Management

The previous chapters have captured the architecture and operational aspects of airports, culminating in the development of a model of the airport surface system used to underpin the research in the rest of this thesis. In order to complete the contextual aspect of this thesis, this chapter addresses the fundamentals of safety and Safety Management Systems (SMS) in six parts.

The first part introduces the concept of safety and the second part is concerned with its measurement and the safety management at a national level. Subsequently, the concept of SMS, its cornerstones, and requirements at the organisational level are introduced. The state of implementation of airport SMS is discussed in the fourth section before part five introduces airport surface safety measures. Finally, part six concludes this chapter.

4.1 Fundamentals of Safety Management

This section discusses in detail safety, within the context of the aviation industry and highlights the necessity of an effective Safety Management System (SMS). The ICAO's Safety Management Manual (SMM) (International Civil Aviation Organization, 2009e) is used as the source for globally accepted definitions related to this safety section (4.1), unless otherwise indicated.

In Chapter 3 airport surface operations were modelled as a socio-technical system, in which people actively interact with technology in order to achieve production goals through the delivery of services. A major characteristic of socio-technical systems is that

hazards, i.e. "condition(s) or object(s) with the potential to cause injuries to personnel, damage to equipment or structures, loss of material, or reduction of ability to perform a prescribed function", are a normal part of their operation.

Hazards are not necessarily damaging, but have the potential to be safety critical. Therefore, their potential effects should be assessed and controlled, for example, by preventing their occurrence in the first place, or by mitigating their consequences. As long as safety risks are kept under a reasonable degree of control the system is considered to be safe. Safety is therefore a concept that encompasses relatives rather than absolutes, i.e. hazards are an integral part of inherently safe systems, and safety risks are acceptable as long as they are controlled.

Hazards can be found in any part of a system and include those associated with design factors (e.g. physical airport surface infrastructure, aircraft, ATC equipment), procedures and operational practices (e.g. inadequacy of procedures for the actual operating conditions), human performance and the work environment (e.g. physical ability to carry out the work, noise, temperature, lighting), and organisational factors (e.g. compatibility of production and safety goals).

Every hazard has a *consequence*, defined as "the potential outcome (or outcomes) of a hazard." These consequences can be damaging and present a risk to safety. In order to prioritise the allocation of resources (e.g. to channel hazard mitigation efforts) it is necessary to evaluate and measure (i.e. quantify) the consequences of hazards. This measure is referred to as *safety risk* and " is defined as the assessment, expressed in terms of predicted *probability* (i.e. "the likelihood that an unsafe event or condition might occur") and *severity* (i.e. "the possible consequences of an unsafe event or condition, taking as a reference the worst foreseeable situation"), of the consequences of a hazard." Examples of ICAO's probability and severity classification are given in Tables 11 and 12.

After the safety risk (i.e. the product of probability and severity) of the consequence of a hazard has been determined, the *tolerability of safety risks* (i.e. "the tolerability of the consequences of hazards") is assessed. This can be determined using a safety risk assessment matrix and subsequently evaluated by means of a safety risk tolerability matrix. Examples of ICAO's safety risk assessment and tolerability matrices are given in Tables 13 and 14. If safety risks are considered to be intolerable, they must be mitigated.

Table 11: Probability classification

Frequency	Meaning	Value
Frequent	Likely to occur many times (has occurred frequently)	5
Occasional	Likely to occur sometimes (has occurred infrequently)	4
Remote	Unlikely to occur, but possible (has occurred rarely)	3
Improbable	Very unlikely to occur (not known to have occurred)	2
Extremely improbable	Almost inconceivable that the event will occur	1

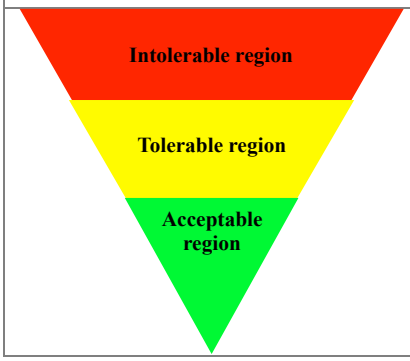
Table 12: Severity classification

Severity of occurrence	Meaning	Value
Catastrophic	- Equipment destroyed - Multiple deaths	A
Hazardous	- A large reduction in safety margins, physical distress or a workload such that the operator cannot be relied upon to perform their tasks accurately or completely - Serious injury - Major equipment damage	B
Major	- A significant reduction in safety margins, a reduction in the ability of the operators to cope with adverse operating conditions as a result of increase in workload, or as a result of conditions impairing their efficiency - Serious incident - Injury to person	C
Minor	- Nuisance - Operating limitations - Use of emergency procedures - Minor incident	D
Negligible	- Little consequences	E

Table 13: Safety risk assessment matrix

Risk probability		Risk severity				
		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Table 14: Safety risk tolerability matrix

Suggested criteria	Assessment risk index	Suggested criteria
	5A, 5B, 5C, 4A, 4B, 3A	Unacceptable under the existing circumstances.
	5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D, 2A, 2B, 2C	Acceptable based on risk mitigation. It may require management decision.
	3E, 2D, 2E, 1A 1B, 1C, 1D, 1E	Acceptable.

The following example illustrates the terms. A wind blowing at 15 knots across a runway is a hazard. One of the consequences of this hazard is a runway excursion, an occurrence whereby an aircraft leaves the paved runway surface, because the pilot is not able to control the aircraft in crosswinds. Runway excursions have occurred occasionally (risk probability) in the past and, at their extreme, can lead to catastrophic accidents (risk severity) with major loss of life and damage to property (Flight safety Foundation, 2009). Therefore, their safety risk is intolerable (ICAO safety risk index category 4A) and runway excursions are unacceptable under the existing circumstances.

In order to bring the safety risks of the consequences of hazards under control, safety risk mitigation strategies must be employed. The words control and safety risk mitigation are used interchangeably in this thesis and refer to measures for mitigating unacceptable levels of safety risk (i.e. achieving an *acceptable level of safety* - ALoS). Intolerable risks must thereby be prioritised. ALoS is defined as "the minimum degree of safety that has been established by the State and must be assured by a State Safety Program (SSP)." Therefore, a system is *safe* as long as the level of risk is within the ALoS.

To summarise, safety risk assessment and mitigation should follow a four-step process:

1. Identification of hazards,
2. Identification of the consequences of hazards,
3. Assessment of the consequences of hazards in terms of probability and severity (the product of probability and severity is the safety risk), and
4. Mitigation of safety risks through the development and implementation of safety risk mitigation strategies.

The aim of this thesis is to assess the safety of airport surface operations and to propose a framework for a holistic airport safety management. The current chapter contributes to

this aim by defining the consequences of hazards to surface operations. At the highest level these are accidents and incidents and this chapter introduces the five main types (excursions (EX), ground collisions (COL), incursions (IN), Foreign Object Damage (FOD), and wildlife strikes (WS)) that can occur on the airport surface. Subsequently, Chapters 5 to 9 determine the hazards (i.e. causal factors) that can lead to these occurrences. As will be shown in Chapter 7, these five accident / incident types occur frequently and, therefore, this thesis focuses on modelling their severity only. The relationship between the severity of occurrences and their underlying causal factors (hazards) is modelled in Chapter 11 and based upon the results, safety risk mitigation strategies are proposed.

This section has introduced the concept of safety and the next addresses the management of safety at a national level, before the subsequent paragraphs introduce the cornerstones of a SMS at the organisational level.

4.2 State Safety Programme

Under the Chicago Convention on Civil Aviation, Annexes 1, 6, 8, 11, 13, and 14, States are required to establish a State Safety Programme (SSP) in order to achieve an ALoS. A SSP is an integrated set of regulations and activities aimed at improving safety, i.e. a system for safety management by the State (International Civil Aviation Organization, 2009e).

4.2.1 Safety Measures

To determine whether a system operates at the ALoS measures and the corresponding targets are required. The measurement of safety involves KPIs together with concrete (quantified) objectives for these KPIs. Once KPIs and safety targets have been defined, the level of safety of a State's aviation system can be established. To do so, values must be attached to the ALoS (e.g. a maximum of five accidents per year and a reduction of incidents by 20.0% within two years) and it is the Sate's responsibility to define the ALoS.

In this context it must be stressed that the notion of ALoS refers to national objectives that are to be achieved through a SSP (International Civil Aviation Organization, 2009e).

4.2.2 Accidents and Incidents

At the State-level, safety measures in aviation are typically KPIs related to accidents and incidents. Common KPIs for airport surface operations include the number of accidents and incidents on the airport surface, such as excursions and incursions (UK Civil Aviation Authority, 2011c). These are discussed in detail in section 4.5.

Accidents and incidents are best defined by ICAO in Annex 13 to the Convention on International Civil Aviation. These definitions (reproduced below) are standard in the aviation industry and are used throughout this thesis as follows (International Civil Aviation Organization, 2001c):

An *accident* is defined as "an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which:

a) a person is fatally or seriously injured […]; or

b) the aircraft sustains damage or structural failure […]; or

c) the aircraft is missing or completely inaccessible."

An *incident* is "an occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation." According to the ICAO, both accidents and incidents are *safety occurrences*.

The common features of accidents and incidents are that they are both unexpected and result in unwanted outcomes. The main difference lies in the characterisation of the outcome. While accidents result in physical damage (or disappearance) of person(s) or infrastructure, incidents refer to situations where the safety of the operations has been affected, but no physical damage was observed (Dupuy, 2012). Thus, the difference lies in the degree of injury sustained by persons, and / or the degree of damage sustained by the aircraft, i.e. the severity of the occurrence.

This assumes a causal chain between accidents and incidents. The concept of the common cause hypothesis was first introduced by Heinrich in the 1930s. Based upon a review of industrial accident reports, Heinrich correlated the occurrence of unsafe acts to the occurrence of accidents with minor injuries, and to those with major injuries. He

concluded that 300 unsafe acts lead to 29 accidents with minor injuries and over time to one accident with major injuries. This implies that unsafe acts, accidents with minor injuries and accidents with major injuries, each have the same causes (Heinrich, 1931). Generalising this concept, it can be said that accidents and incidents share the same causes and that a large number of incidents will lead over time to a smaller number of accidents. A ratio between accidents and incidents for ATM operations has not been proposed, although, some studies indicate that in systems with robust safety defences, such as aviation, dozens of incidents occur for every accident (Phimister*, et al.*, 2004). In order to establish a ratio between accidents and incidents their frequencies must be known. Reliable numbers on the frequency of accidents can be gathered from national Accident Investigation Boards. Determining the number of incidents for a country would require a holistic data set that combines the perspectives of all relevant aviation stakeholders. Chapter 6 discusses whether such databases exist, and in particular section 6.5.4.3, addresses the question whether a ratio between accidents and incidents in ATM operations can be calculated.

It follows from the discussion above that the mitigation of the causes underlying safety occurrences will serve likewise to mitigate both incidents and accidents. This research, therefore, considers both. According to Heinrich, this assumes that there is a significant relationship between accidents and incidents and Chapter 11 (section 11.2.2.1) will test whether this assumption holds true.

4.3 Safety Management Systems

Part of the State's SSP requires aviation organisations, including approved training organisations, international aircraft operators, approved maintenance organisations, organisations responsible for type design and / or manufacture of aircraft, air traffic service providers and certified aerodromes, to implement a Safety Management System (SMS). The SMS is a tool for the management of safety at the organisational level and the following paragraphs present its concept (International Civil Aviation Organization, 2009e).

4.3.1 Concept and Regulatory Anchoring

The legislative framework for the implementation of SMS is set by the ICAO (Annexes 1, 6, 8, 11, 13 and 14), multi-national safety organisations (e.g. EUROCONTROL Safety Regulatory Requirement (ESARR) 3 – Use of Safety Management Systems by ATM Service Providers), and national regulatory bodies (e.g. FAA Advisory Circular 120-92A Safety Management Systems for Aviation Service Providers) (Federal Aviation Administration, 2010a; International Civil Aviation Organization, 2009e; The European Organisation for the Safety of Air Navigation, 2010c).

The requirement for aviation safety organisations to implement a SMS, together with the importance of the public's perception of aviation safety, necessitates the management of safety as a core business function for aviation service providers, and thus the implementation of a dedicated Safety Management System. A SMS is a systematic approach to managing and improving safety, including policies and objectives, operational risk management and adequate control mechanisms. It is a framework that provides an organisation with the tools necessary to ensure that any drift by the organisation towards a lower safety performance is prevented (International Civil Aviation Organization, 2009e).

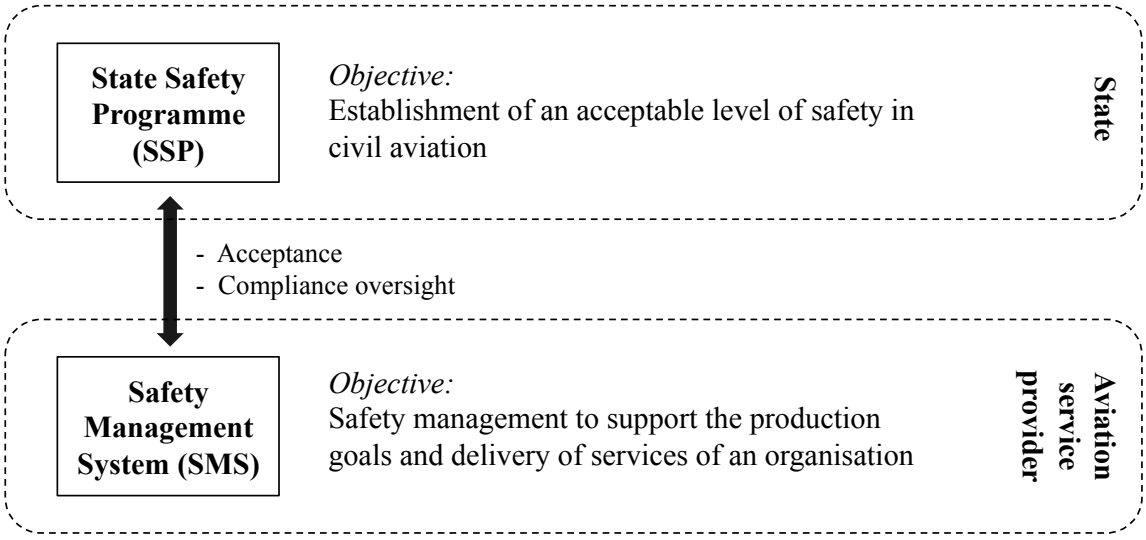


Figure adapted from International Civil Aviation Organization (2009e)

Figure 29: Relationship between SSP and SMS

An SMS derives from an SSP: it is the State's responsibility to develop and implement a SSP with the objective of achieving an ALoS. As part of the activities of the SSP, the State is responsible for approving and overseeing the development, implementation and

operational performance of SMS for aviation service providers (International Civil Aviation Organization, 2009d). Figure 29 summarises the relationship between safety management at the State and service provider level, while the next section introduces the ICAO's SMS framework in detail.

4.3.2 ICAO SMS Framework

A SMS provides the toolbox for an effective safety management at the organisational level. It provides the tools to control the safety risks of the consequences of hazards that aviation organisations face during their operations. The design of a SMS must be organisation-specific and must reflect the needs of the individual service provider.

SMS is a systematic approach to safety that strives to assess and continuously improve the safety of an entire system. It therefore requires the assessment of all system components and their interactions for hazards and associated safety risks. The management of safety comprises two core operational processes or activities: safety risk management, and safety assurance. A SMS consists of four components that represent the two core operational processes and their supporting organisational arrangements. The four SMS cornerstones contain a total of twelve elements in the areas of planning, achievement, assurance and promotion. Together, they comprise the ICAO SMS framework (International Civil Aviation Organization, 2009e) as shown in Figure 30.



Figure derived from International Civil Aviation Organization (2009e)

Figure 30: ICAO SMS framework

Whilst the SMS realisation in the U.S. maps 100.0% to the ICAO framework described above, there are variations in the realisation of the SMS in other jurisdictions. For example, the SMS standard developed by EUROCONTROL and the Civil Air Navigation Service Organisation (CANSO), a global association of ANSPs working on the improvement of air navigation services, contains four components with only ten elements. In addition, a central role is given to safety culture as a 'system enabler' (The European Organisation for the Safety of Air Navigation SKYbrary, 2012c).

Although components and elements may be classified differently, the basic concept remains the same. A "SMS results in the design and implementation of organisational processes and procedures to identify safety hazards and their consequences and bring the

associated safety risks in aviation operations under the control of the organisation" (International Civil Aviation Organization, 2009e).

In this thesis the global SMS standard, as defined in the ICAO's Safety Management Manual (SMM), is adopted and used as a reference to introduce the SMS and its cornerstones (sections 4.3.2.1 – 4.3.2.6). The following sections expand on the details of this framework.

4.3.2.1 SMS Prerequisites

Given its systematic nature, the first prerequisite for the development of a SMS is the system description in terms of its components and their interactions (in this case the airport system model developed in Chapter 3). Such a baseline system can then be used to identify the vulnerabilities of human actors, other components and their interfaces.

4.3.2.2 Safety Policy and Objectives

The management of safety is a top-down approach, in which the senior management of the organisation is responsible for the development, implementation and compliance of the SMS. The safety *management commitment and responsibility* function is therefore essential for the success of every SMS. It starts with the development of the *safety policy and objectives* of the organisation by its senior management. The Accountable Executive, who has the final responsibility for the effective and efficient performance of the organisation's SMS and ultimate accountabilit*y*, must sign the policy. The safety policy should reflect the organisation's commitment regarding safety and should contain a clear statement about the provision of the necessary resources for its implementation. This includes, for example, safety reporting procedures, or types of operational behaviour that are considered unacceptable. Most importantly, the safety policy must be communicated throughout the organisation.

The organisation should also identify the *accountabilities* of all management members and employees with respect to the safety performance of the SMS. Responsibilities, accountabilities and authorities (e.g. to make decisions regarding the safety risk tolerability) should be documented and communicated throughout the organisation. In addition, the *appointment of key safety personnel* is crucial for the successful

implementation of a SMS. In this context, a safety manager should be the responsible individual and focal point for the implementation and maintenance of the SMS.

After the safety policy has been defined and key safety personnel and accountabilities assigned, the organisation develops a SMS implementation plan. This defines the organisation's approach to safety management in a manner that meets the organisation's safety objectives while supporting an effective and efficient delivery of services.

The process of developing a SMS must be documented clearly. The most important piece of the *SMS documentation* is the SMS manual (SMSM), which is a key instrument for communicating the organisation's approach to safety and should document all aspects of the SMS, including the safety policy and objectives, processes and procedures, accountabilities, responsibilities and authorities.

Finally, although the aim is to control safety risks, an organisation needs to be prepared for the worst foreseeable situation, i.e. the occurrence of an accident. Therefore, every service provider must have an *emergency response plan* to facilitate the timely and appropriate response to occurrences and must coordinate this plan with those organisations it interacts with during the provision of its services.

4.3.2.3 Safety Risk Management

At the core of a SMS is the *safety risk management* that supports the development of evidence-based measures for the overall safety management process. The aim is to control the safety risks of the consequences of hazards in critical activities to a level as low as reasonably practicable (ALARP). Safety risk management consists of two distinct activities: i) *hazard identification*, and ii) *safety risk assessment and mitigation*. In practical terms, safety risk management is concerned with reporting and data collection, investigation, data analysis and the mitigation of safety risks.

A mature safety risk management strategy should combine reactive, proactive and predictive elements. Reactive methods respond to occurrences that have already happened, such as accidents and incidents. Proactive methods on the other hand look actively for the identification of hazards and associated safety risks, while predictive methods capture system performance as it happens in real-time normal operations to identify potential failure problems.

Safety risk management must be supported by the routine collection of safety data. This includes the collection of historical accident and incident data, the identification of hazards, and the collection of operational data on a daily basis in order to feed reactive, proactive and predictive methods. The collection of historical occurrence data requires the implementation of effective reporting schemes. This needs to be supported by the active promotion through the organisation and senior management of an open reporting culture. Reporting procedures should be anchored in the organisational safety policy and be easily accessible for the whole organisation. The central role and importance of reporting systems for SMS is discussed further in section 4.3.2.6. Besides the collection of accident and incident data, the organisation must also ensure adequate investigation of both accidents and incidents in order to identify the causes underlying their occurrence.

The identification of hazards in the context of safety risk management uses the description of the system. The system's components and interfaces are analysed for the presence of hazards and their potentially damaging consequences identified. In addition, a SMS should collect operational data to monitor the performance of real-time operations in order to detect deviations from normal as early as possible.

The collected data are analysed using adequate methodologies and tools (e.g. statistical analysis), to allow the prioritisation of safety risks. Based upon this analysis, safety risk mitigation strategies are developed and implemented with the objective of controlling safety risks to a level ALARP.

4.3.2.4 Safety Assurance

Safety risk management requires constant feedback on its performance. This is delivered through the *safety assurance* function of SMS, which includes *safety performance monitoring and measurement*, *management of change*, and the *continuous improvement of the SMS*.

The primary task of safety assurance is control, requiring the continuous monitoring and evaluation of the performance of the SMS and, in particular, the safety risk management. If changes are necessary, their requirements are fed back to the safety risk management process. In addition, safety assurance provides stakeholders with an indication of system safety performance.

In order to monitor and measure the safety performance of an organisation, KPIs and targets must be defined and the organisational safety performance must then be verified in reference to these. Safety measures should capture the performance of the operational safety risk management, including the effectiveness of operational procedures or safety risk controls. In addition, the elements falling under the safety policy and objectives cornerstone must be monitored. This is to ensure that safety responsibilities and accountabilities are assigned and that the SMS is documented as required.

In addition to the constant monitoring and evaluation of the system's safety performance, an organisation should develop and maintain a formal process to identify changes in the organisation that may affect the established processes and services. The aviation industry, in particular, is fast moving and service providers experience permanent change due to expansion, changes to existing systems, equipment, programmes and services, or the introduction of new equipment and procedures. As change can introduce new hazards, the appropriateness of existing safety risk management processes and safety risk controls must be verified. A formal change management process should identify organisational changes and their implications and the organisation must ensure effective safety risk controls before, during and after the implementation of these changes. This includes the adjustment of safety risk controls to changes in the operational environment and the elimination of controls that are no longer needed or effective.

Finally, an effective SMS must continuously strive for improvement. An organisation should develop and maintain processes to identify the causes of substandard performance, to determine the implications for its operations of a degraded SMS performance, and to eliminate or mitigate such causes.

4.3.2.5 Safety Promotion

The safety policy and objectives, safety risk management and safety assurance components provide the functional framework of a SMS. However, the strict implementation of safety policies, procedures and processes is not enough for the effective management of safety. These three components must be supported by a positive organisational safety culture that creates an environment of trust and advocates safety on all levels (i.e. from senior management to operational personnel).

An organisational culture reflects the value system of an organisation. In particular, the safety culture reflects the values, beliefs and behaviours of an organisation towards safety. A safety culture is created at the organisational level and must be developed top-down. The commitment of the senior management and the Accountable Executive to SMS and its promotion is key for the establishment of a positive safety culture. The organisation and its management are therefore the major determinants of the behaviour employees engage in while performing operational activities. The organisational culture can be affected by factors such as safety objectives, policies and procedures, employee's training and motivation, and the organisation's response to unsafe behaviour. For a SMS to be effective an organisation should create a just culture in which human deviation is not punished, and which aims to encourage an open reporting of incidents. A clear line is drawn, however, such that wilful violations are not tolerated (International Civil Aviation Organization, 2009e). Such a culture relies on a high degree of trust and respect between operational personnel and management. The staff must believe that they will be supported in any decisions they make in regards to safety. Likewise, the staff must understand that intentional breaches of safety that jeopardize operations are not tolerated.

To create a positive safety culture an organisation must actively promote safety. The *safety promotion* cornerstone includes the two key elements of *training and education* and *safety communication*. To support the former, an organisation should develop and maintain a safety training programme that ensures that all personnel are trained and competent to perform the SMS duties. The scope of the safety training varies depending on the involvement of the individual in the safety management process. The provision of training to all staff, regardless of their level in the organisation, is an indication of management commitment to safety and SMS. The safety training standards for operational personnel, managers and supervisors, as well as senior management and the Accountable Executive should be documented in the SMS manual.

The communication of the importance of safety and its management is a critical element for the success of a SMS and the creation of a just culture. The organisation should communicate the SMS objectives and procedures to all operational personnel and the SMS should be visible in all aspects of an organisation's operations. The safety manager is responsible for communicating the SMS throughout the organisation with the aim of actively encouraging operational personnel to identify and report hazards. Safety communication, therefore, aims to ensure that all employees are fully aware of the SMS, to

convey safety-critical information, to explain why particular actions are taken, and finally why safety procedures are introduced or changed.

4.3.2.6 The Importance of Safety Data

As introduced in section 4.3.2.3 on safety risk management, SMSs are data-driven and, therefore, rely on the collection of safety data. The SMS safety data cycle starts with the collection and analysis of data. Based upon this analysis, safety risks are prioritised and controlled through mitigation measures. Likewise, the results from the safety data analysis can contribute to the development of the organisational safety strategy, e.g. the setting of safety targets. Once safety risks are under organisational control, their effective mitigation is monitored against the established targets. This is achieved through a continuous process of data collection and analysis with the aim of detecting at an early stage any degradation of the system's safety performance. If the system performs at a substandard level, the collected data feeds back into the safety risk management process in order to bring the identified areas of concern under control. The effective collection of safety data is supported by the promotion of an open reporting and positive safety culture.

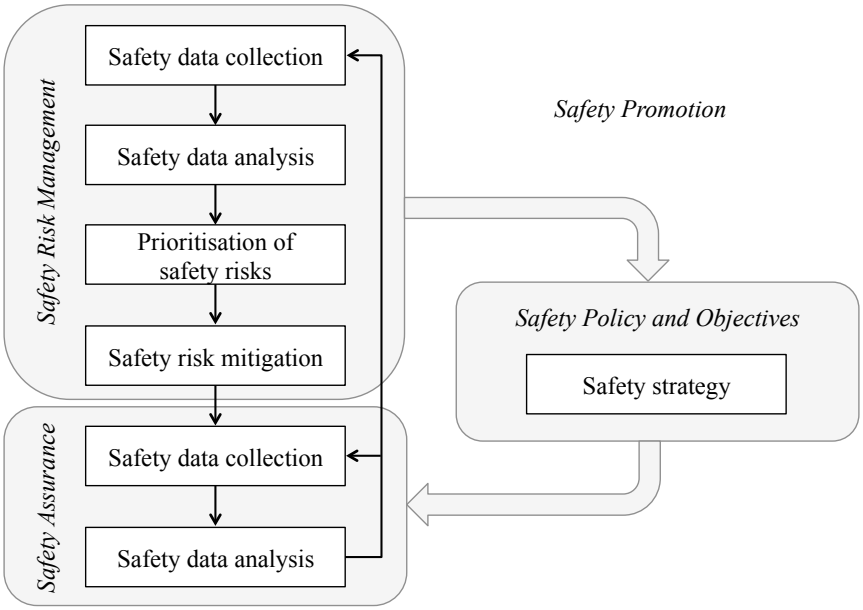


Figure 31: The safety data cycle

Figure 31 summarises the safety data cycle and highlights the central role and importance of safety data across the four components of the SMS. The selection of the

safety data to be collected based upon definitions for accident / incident types, the data collection techniques, methods of investigation, as well as analytical data analysis methodologies and tools, are critical elements for a successful SMS. Therefore, the next chapter reviews how state-of-the-art efforts for airport surface safety analysis and risk mitigation comply with these requirements.

Although the importance of safety data is emphasised, little guidance on the collection of safety data is provided in the SMS framework. The ICAO Annex 13 requires States to report and investigate accidents and serious incidents[2] (International Civil Aviation Organization, 2001c). However, "there is no obligation for States to conduct an investigation into an incident" (International Civil Aviation Organization, Year not specified). The extent to which incidents are reported is up to the individual States and aviation service providers. Regulatory bodies at a national level often mandate the collection of all occurrences that may or may not affect the level of safety. Therefore, when dealing with safety data, it is important to analyse countries that promote the reporting of all safety occurrences.

In addition to national regulations, organisations may define their own reporting requirements. The quality of safety data collected at the organisational level is dependent on the appropriateness of the reporting system and the organisational safety culture. Drivers for effective safety reporting include:

- Willingness: of operational personnel to report.
- Information: The training of operational personnel to recognise hazards and to understand their consequences. This includes human, technical and organisational factors that can challenge the safety of the system.
- Flexibility: The ability of operational personnel to adapt hazard reporting when facing unusual circumstances, thus allowing information to reach the appropriate decision-making level quickly.
- Learning: The competence of operational personnel to draw conclusions from safety information systems.
- Accountability: The encouragement of operational personnel to provide safety information related to hazards, but with a clear line that differentiates between acceptable and unacceptable operational performance.

[2] Serious incident: "An incident involving circumstances indicating that an accident nearly occurred" (International Civil Aviation Organization, 2001c)

4.4 Airport SMS

The previous section introduced the ICAO SMS framework that is applicable to all aviation stakeholders and the following paragraphs discuss the status of its implementation for airports in particular.

Since November 2005, Annex 14 of the Convention on International Civil Aviation (Annex 14) requires certified aerodromes to have a SMS in operation (International Civil Aviation Organization, 2004b). Although Annex 14 provides the global legislative framework, regulations have yet to be established at the State-level. For example, currently, there is no regulatory requirement for airport operators in the European Union (EU) (i.e. EASA member states that comprise a total of 37 self-regulatory bodies, 27 from European countries and nine from non-European countries) and the U.S. to implement a SMS.

EASA is responsible for the regulation and implementation of SMS at the European level. The first requirements for aviation service providers (e.g. airlines) to implement a SMS were published in 2012 (e.g. Regulation (EC) 290/2012 SMS requirement for flight and cabin crew). However, the EU rules for SMS for airport operators are still under development. EASA issued the notice of proposed amendment (NPA) 2011-20 ‘Authority, Organisation and Operations Requirements for Aerodromes’ in December 2011 for consultation with responses to the proposed law closing on in February 2013. The EU regulation is expected to be issued by the end of 2013 (European Aviation Safety Agency, 2013b).

Likewise, in the U.S., the FAA issued a notice of proposed rulemaking (NPRM) for SMS for certified aerodromes in October 2010. Airports and other service providers were given the opportunity to comment on the NPRM up until March 2011. Since the FAA received an extensive amount of comments, it decided to modify the proposal and to provide another opportunity for public comments. The revised NPRM is now expected to be published in December 2013 with a 60-day comment period (Federal Aviation Administration, 2013c).

Therefore, the rulemaking for the implementation of SMS for airport operators is yet to be finalised. In addition to missing regulations, there is little guidance on how in practice to develop and implement a SMS for airport operators. While the ICAO’s Safety Management Manual introduces the general concept of SMS and its elements for all

service providers, it lacks detailed guidelines on how to design a SMS effectively. To support the implementation of SMS, the ICAO is currently developing a new Annex (Annex 19) which consolidates Standards and Recommended Practices (SARPs) for safety management requirements. This is supposed to be adopted in November 2013 (European Aviation Safety Agency, 2013b).

At the European level, the published NPA 2011-20 is a draft law that specifies the requirement for certified aerodromes to implement a SMS, although without providing any guidance on how to establish and implement one in practice. However, the European Commercial Aviation Safety Team (ECAST), a partnership among EASA, national European regulatory bodies and the aviation industry, established a working group to give direction on SMS and safety culture. The available materials provide a good introduction to the topics of safety culture, organisational structures, hazard identification and operational risk management. Nevertheless, they are designed for general SMS and lack specific guidance and examples on how to design and implement SMS for airport operators (European Commercial Aviation Safety Team, 2011). Regulators at a national level have regularly announced the requirement for the future implementation of SMS. In so doing, they commonly provide an introduction to SMS and its components, but yet again without specifying detailed requirements (e.g. UK Civil Aviation Authority, 2013; Luftfahrt-Bundesamt, 2008).

In the U.S., meanwhile, the FAA issued Advisory Circular (AC) 150/5200-37 which provides an introduction to SMS for airport operators, but again is limited to the concept of SMS and its cornerstones (Federal Aviation Administration, 2007b). However, 30 airports to date have developed and implemented a SMS voluntarily. The lessons learned from these airport SMS pilot studies are publically available and help to provide feedback on the experiences of airport operators and the challenges they faced during implementation. The available reports, however, mainly serve to highlight deficiencies in the concept of SMS rather than translating them into useful guidance on how to do it right (Federal Aviation Administration, 2011c). In addition, the Transportation Research Board's (TRB) Airport Cooperative Research Program (ACRP) developed a guidebook that explores what constitutes an airport SMS. The report outlines in detail the SMS elements, recommended practices for their implementation, and provides practical examples on 'how to do it' (Airport Cooperative Research Program, 2009).

In summary, SMS is increasingly important and a core business function for future airport operations. Although their importance is widely promoted and their general concept

understood, the necessary regulations are still to be passed and practical guidance on SMS development and implementation is rare. Airport SMS currently seems to be more of a conceptual construct rather than a toolbox that is ready for implementation. Therefore, the development of robust tools to support the effectiveness of SMS is important and this thesis addresses this need.

4.5 Airport Surface Safety

The aim of SMS is to manage safety risk to be ALARP and within ALoS. At the highest level, this means the avoidance of accidents and incidents. A review of accident / incident statistics (European Aviation Safety Agency, 2013a) highlighted that five occurrence types are a major concern for airport surface operations. Therefore, this thesis considers these five types: excursions (EX), ground collisions (COL), incursions (IN), Foreign Object Damage (FOD), and wildlife strikes (WS).

4.5.1 Excursions

A runway excursion happens when an aircraft exits the runway, either to its side or at the end. Excursions can occur during landing as well as take-off. For example, a tyre burst during touchdown can lead to a loss of control over the aircraft, which in return may result in an excursion. Excursions can also occur on taxiways, e.g. if an aircraft slips off the paved surface while turning.

At their extreme, excursions can lead to damage to aircraft, major injuries or loss of life. Such a case occurred on 20 December 2008 at Denver International Airport when Continental Airlines flight 1404 departed the left side of runway 34R during take-off (Figure 32). The captain and five passengers were seriously injured and the aircraft was substantially damaged during the excursion and post-crash fire. During take-off the aircraft encountered a strong and gusty crosswind that exceeded the captain’s training and experience and the detailed investigation of these causes is given in the National Transportation Safety Board (2010a) accident report.



Source: Aviation Safety Network (2013)

Figure 32: Runway excursion Denver 2008

Excursions can also result in an incident with no injuries and no damage to the aircraft, as seen with the excursion that occurred on 3 November 2011 in Munich (Figure 33) (Bundesstelle fuer Flugunfalluntersuchung, 2011).



Source: Bundesstelle fuer Flugunfalluntersuchung (2011)

Figure 33: Runway excursion Munich 2011

A major challenge in the aviation industry is a lack of both standardised and complete definitions for different accident and incident types (Table 15).

Table 15 shows the lack of standardised definitions relating to excursions, across regulatory bodies and major aviation safety initiatives. In addition, these definitions are incomplete as they do not always consider taxiway excursions. Occurrences on taxiways

can equally cause major disruptions to surface operations, e.g. when the surface needs to be closed to recover an aircraft that has left the paved surface. For example, on 13 March 2012, a Delta jet rolled off the taxiway at Atlanta Hartsfield - Jackson International Airport (Figure 34). The aircraft had no passengers on board but sustained substantial damage and had to be recovered by emergency crews (My Airport Operations, 2012).



Source: My Airport Operations (2012)

Figure 34: Taxiway excursion Atlanta 2012

Table 15: Runway excursion definitions

Organisation	Definition	Limitations
• Flight Safety Foundation (FSF) Reducing the risk of runway excursions (Flight Safety Foundation, 2009)	"Runway Excursion: When an aircraft on the runway surface departs the end or the side of the runway surface. Runway excursions can occur on take-off or landing. They consist of two types of events: -Veer Off: A runway excursion in which an aircraft departs the side of a runway. -Overrun: A runway excursion in which an aircraft departs the end of a runway."	• Undershoots (i.e. situations in which the aircraft undershoots the intended runway threshold) are not included • Negligence of taxiway occurrences
• Commercial Aviation Safety Team (CAST) / ICAO Common Taxonomies (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2008b) • ICAO ADREP (International Civil Aviation Organization, 2006a) • EASA European Coordination Centre for Accident and Incident Reporting Systems (ECCAIRS)	"A veer off or overrun of the runway surface."	• Undershoots are not included • Negligence of taxiway occurrences
• European Action Plan (The European Organisation for the Safety of Air Navigation, *et al*, 2013) referring to ICAO/ECCAIRS	"A runway excursion is the event in which an aircraft veers off or overruns the runway surface during either take-off or landing."	• Undershoots are not included • Negligence of taxiway occurrences
• International Federation of Airline Pilots' Associations (IFALPA) Runway Safety Manual (The International Federation of Air Line Pilots' Associations, 2009)	"A runway excursion is defined as when an aircraft departs the runway either by veering off the side or by overrunning the runway end."	• Undershoots are not included • Negligence of taxiway occurrences
• FSF Approach and Landing Accident Reduction (ALAR) toolkit (Flight Safety Foundation, 2000)	"Runway excursions occur when: i) aircraft veer off the runway during the landing roll; and, ii) aircraft veer off the runway or taxiway when exiting the runway. Runway overruns occur when the aircraft roll-out extends beyond the end of the landing runway."	• The definition separated between excursions and overruns • Overruns are considered as separate occurrence • Excursions during take-off and undershoots are not included

The Australian Transport Safety Bureau (ATSB) currently gives the most complete definition for excursions. It defines a runway excursion "as an occurrence (accident or incident) where an aircraft on the ground departs from a runway or taxiway. Excursions may occur on take-off, taxiing or landing, and can be either intentional or unintentional" (Australian Transport Safety Bureau, 2008b). Although this definition encompasses all possible excursion scenarios, it is classified as a 'runway excursion'. This terminology seems inappropriate and should be generalised to include excursions from taxiways. Therefore, the ATSB definition is adapted in this thesis as follows:

Excursion. An occurrence (accident or incident) where an aircraft on the ground departs from a runway or taxiway. Excursions may occur on take-off, taxiing or landing, and can be either intentional or unintentional (Definition adapted from Australian Transport Safety Bureau, 2008b).

The ATSB definition does not differentiate between different types of excursions. To allow overruns, undershoots and veer-offs to be compared, the following definitions apply:

- *Overrun:* An excursion in which the aircraft departs the end of a runway or taxiway.
- *Undershoot:* An excursion in which the aircraft undershoots the intended runway or taxiway threshold.
- *Veer off:* An excursion in which an aircraft departs the side of a runway or taxiway (Definition adapted from Flight Safety Foundation, 2009).

4.5.2 Ground Collisions

Ground collisions happen when two aircraft, an aircraft and a V/PD, or an aircraft and another obstacle on the airport surface collide. Well-known examples from history include the Tenerife airport disaster in 1977, in which two Boeing 747 aircraft collided on the runway resulting in 574 fatalities (Raad Voor De Luchtvaart. Netherlands Aviation Safety Board, Year not specified), and the Linate airport disaster in October 2001 (Figures 35 and 36), in which a Scandinavia Airlines flight collided on take-off with a Cessna business jet killing 114 people on board of both aircraft and 4 on the ground (Agenzia Nazionale Per La Sicurezza Del Volo, 2004).



Source: British Broadcasting Corporation (2001)

Figure 35: Linate airport disaster 2001



Source: AirDisaster.com (2013)

Figure 36: Wreckage at Linate airport 2001

The definitions used for ground collisions are also ambiguous and Table 16 contains a selection of some those commonly used. The most commonly used definition in the industry is provided by CAST / ICAO's Common Taxonomy Team. However, the definition is limited in the following respects:

- It excludes collisions on runways. Such events would be classified as runway incursions, which, as shown in the next section, refer to situations involving the incorrect presence of either an aircraft, or V/PD on the runway. The runway incursion definition does not explicitly include collisions making it difficult to classify a collision on a runway using the definitions provided by CAST / ICAO.
- Occurrences cannot be classified exclusively. For example, the definition for ground collisions includes encounters with animals. However, CAST / ICAO provides a separate definition for the occurrence category 'Bird' that refers to 'occurrences involving collisions / near collisions with bird(s) / wildlife'. Therefore, it is not clear, which definition to use to classify collisions involving wildlife (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2008b).

To avoid ambiguity, ground collisions are defined as follows throughout this thesis:

Ground collision. Collision on the airport surface. The definition refers to collisions between aircraft or V/PD with another aircraft or V/PD, obstacle, building, or fixed structure while on the airport surface (Definition adapted from Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2008b).

Table 16: Ground collisions definitions

Organisation	Definition	Limitations
• CAST / ICAO Common Taxonomies (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2008b) • ICAO ADREP (International Civil Aviation Organization, 2006a) • EASA Annual Review referring to CAST/ICAO	"Collision while taxiing to or from a runway in use. Usage notes: Includes collisions with an aircraft, person, animal, ground vehicle, obstacle, building, structure, etc., while on a surface other than the runway used for landing or intended for takeoff."	• The definition excludes collisions on runways • The definition mixes other occurrence types (e.g. wildlife strikes) with ground collisions
• EUROCONTROL Harmonisation of European Incident Definitions Initiative (HEIDI) (The European Organisation for the Safety of Air Navigation, 2001b)	"Ground-ground collision: collision taking place between two aircraft, objects, vehicle, persons, animals standing or moving on the ground or any combination thereof."	• The definition mixes other occurrence types (e.g. wildlife strikes) with ground collisions

4.5.3 Incursions

A runway incursion happens when an aircraft, vehicle, or pedestrian infringes onto the runway without obtaining prior clearance. Similarly, taxiway incursions refer to situations in which an aircraft or V/PD resides in an incorrect position on a taxiway. The mitigation of such incidents is important since, in extreme situations, incursions can result in a ground collision leading to major loss of life. Hence, incursions are precursors (i.e. an event in the accident chain (Phimister*, et al.*, 2004)) to ground collisions.

In the past, there were many definitions of what constituted an incursion (e.g. Australian Transport Safety Bureau, 2004; Federal Aviation Administration, 2004; The European Organisation for the Safety of Air Navigation, 2001a). The importance of runway incursions and their damaging potential was increasingly recognised in the aviation community and the need for a global definition of runway incursions was finally accepted at the 11th Air Navigation Conference in Montreal in 2003 (International Civil Aviation Organization, 2007). Consequently, on 27 April 2006, the ICAO released the definition of a runway incursion as: "any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take off of aircraft" (International Civil Aviation Organization, 2007).

This new definition was accepted by the industry and aviation stakeholders, and where necessary changes have been made to comply with the ICAO standard (e.g. the UK CAA adopted the ICAO's definition on 1 January 2007 (Goodman and Fraser, 2011) and the FAA on 1 October 2007 (Federal Aviation Administration, 2009c)).

Nonetheless, the ICAO's definition is limited. It does not include incidents on taxiways, although taxiway collisions occur frequently. Recent examples include e.g. the collision of two aircraft at Dulles International Airport in August 2012 (American Broadcasting Company News, 2012), the collision of two jets at Boston Logan International Airport in July 2011 (CBS Broadcasting. Inc. Boston, 2011), and the collision of two planes on a taxiway at New York's John F. Kennedy International Airport in April 2011 (CBS Broadcasting Inc. News, 2011). Furthermore, incursions on taxiways are not always acknowledged by the aviation stakeholders and this can be attributed to the lack of guidance from the ICAO. However, there are some adhoc definitions including the definition of taxiway incursions in EUROCONTROL's HEIDI taxonomy (The European

Organisation for the Safety of Air Navigation, 2012) and the definition of surface incidents used by the FAA (Federal Aviation Administration, 2010c).

As this thesis addresses all occurrence types on the airport surface, an incursion is defined as follows:

Incursion. Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the maneuvering area (Definition adapted from International Civil Aviation Organization, 2007).

4.5.4 Foreign Object Damage

The common understanding of Foreign Object Damage (FOD) is less controversial. FOD at an airport refers to the damage caused by an object at an inappropriate location at the airport.

The most well-known example of the consequences of a FOD is the crash of the Concorde in July 2000 at Charles de Gaulle airport in Paris in which 113 people died (Figure 37). The accident was caused by a piece of titanium debris (a part of a thrust reverser that fell from an aircraft four minutes earlier) on the runway (Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile, 2002).



Source: The Wall Street Journal (2012)

Figure 37: Concorde crash 2000

Whilst there is a common understanding of FOD, its definitions in the literature are ambiguous and confusing. For example, there is a need to distinguish between Foreign Object Debris and Foreign Object Damage, although both are currently referred to as FOD. Therefore, this thesis streamlines the definitions as follows:

- *Foreign Object (FO) or Foreign Object Debris.* Any object located in an inappropriate location in the airport environment that has the potential to damage aircraft, vehicles, persons, equipment, or otherwise diminish safety (Definition adapted from Federal Aviation Administration, 2010b).

- *Foreign Object Damage (FOD)*. Any damage attributed to a foreign object that can be expressed in physical or economic terms which may or may not degrade the product's required safety and / or performance characteristics (Definition adapted from Federal Aviation Administration, 2010b).

These definitions have been adapted from the FAA and encompass damage to all infrastructure and persons to be found on the airport surface. In addition, the terms Foreign Object (FO) and Foreign Object Damage (FOD) are distinguished clearly in order to avoid any ambiguity in the classification of occurrences.

4.5.5 Wildlife Strikes

Wildlife strikes refer to collisions between aircraft and animals. A major concern for aircraft operators is birds. A collision between an aircraft and a bird is known as bird strike. Figures 38 and 39 illustrate the extent to which birds can present a safety risk to air transport.



Source: Smithsonian (2007)

Figure 38: Bird hazard I



Source: European Cockpit Association (2010)

Figure 39: Bird hazard II

Bird strikes can cause structural damage to aircraft, or engine ingestion which may result in an engine failure or loss of control over the aircraft (The European Organisation for the Safety of Air Navigation SKYbrary, 2013a). At their extreme they can result in an accident, as occurred on 15 January 2009 in New York. US Airways flight 1549 from LaGuardia airport New York to Charlotte / Douglas International Airport struck a flock of Canada geese during its initial climb out. The aircraft lost engine power and ditched into the Hudson River (Figures 40 and 41). Fortunately, all 155 people on board survived (National Transportation Safety Board, 2010b).



Source: Time Inc. (2009)

Figure 40: Hudson River crash 2009 I



Source: Time Inc. (2009)

Figure 41: Hudson River crash 2009 II

Industry initiatives often focus on the control of hazards associated with birds and provide a corresponding definition of wildlife strikes as, uniquely, bird strikes (e.g. Australian Transport Safety Bureau, 2008a; EASA (Maragakis, 2009); International Civil Aviation Organization, 2009a). Wildlife strikes, however, are not limited to birds. In particular, strikes involving large animals on the airport surface have the potential to cause severe damage. An analysis of safety data conducted in in this thesis (Chapter 7 e.g. section 7.3.3) has identified problems associated with animals such as cows, sheep and deer. Therefore, this thesis considers wildlife strikes in general.

Other definitions are ambiguous in their scope and usage. For example, the CAST / ICAO's Common Taxonomy Team provides a definition for the occurrence category 'Bird' and defines them as "occurrences involving collisions / near collisions with bird(s) / wildlife". In addition, CAST / ICAO provide an extra occurrence classification called 'Runway Incursion – Animal', which "includes encounters with wildlife on a runway in use" (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2008b). The inexplicit and confusing nature of such

occurrence classifications makes the analysis and interpretation of wildlife strike data difficult. For instance, Transport Canada's Annual Wildlife Strike report aims to provide "a summary of all Canadian wildlife strike statistics in Canadian Airports" (Transport Canada, 2010b). However the only definition given in the report refers to bird strikes. Mammal strikes are listed, but without the provision of an appropriate definition.

Given the limitations above and to capture the safety risk of all occurrences associated with wildlife, the following definition is used throughout this thesis:

Wildlife strike. A collision between an aircraft and an animal (Definition adapted from Krokos and Baker, 2005).

4.5.6 Interactions

The accident and incident types introduced in this chapter do not occur in isolation. In fact, they interact in a complicated manner and one type of accident / incident can cause another. These interactions are captured graphically in Figure 42.

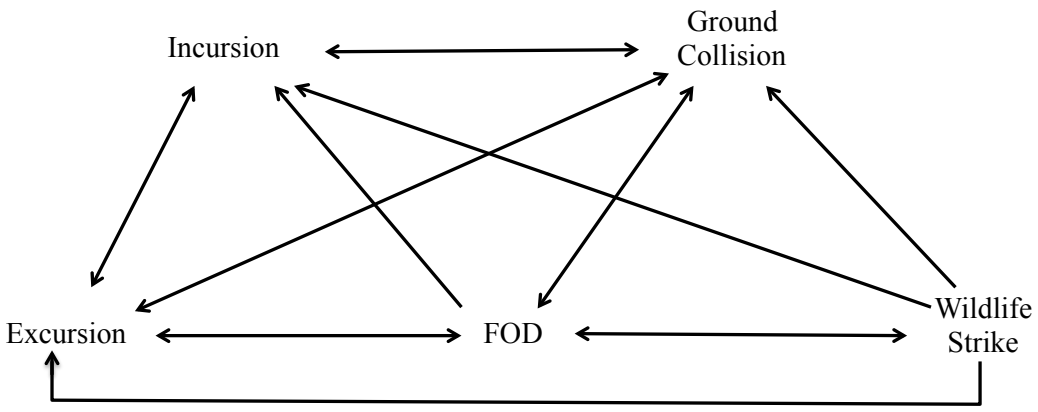


Figure 42: Interaction of occurrences

An aircraft infringing onto a runway can cause the excursion of a landing airplane, for instance, if the pilot initiates an avoiding manoeuvre. Incursions at their extreme can cause a ground collision. Similarly, an aircraft that veers off the surface may collide with another aircraft or vehicle on the ground. After a ground collision has occurred, the airport surface needs to be checked for FO that may disrupt operations. Debris can also be the remains of an excursion or wildlife strike and may result in FOD. The results of an analysis of safety

data have revealed a total of 17 interactions between the occurrence types. The details of these are discussed further in section 8.2.1 of Chapter 8. In the context of SMS this means that all accident / incident types and their interactions should be considered.

4.6 Summary

This chapter has introduced the concept of safety and Safety Management System (SMS) and the state of implementation of SMS for airports. It highlighted that airport SMS is currently more of a conceptual construct with regulations still under development and very little guidance regarding practical deployment and implementation. Therefore, the development of robust data-driven tools for the management of airport surface safety is essential and will be addressed in this thesis.

Furthermore, it has been shown that the industry is characterised by definitions that are either missing, incomplete, or not standardised. The inadequacy of definitions is problematic for SMS that aims to capture all hazards and associated safety risks. If safety measures cannot be clearly defined, and thus do not take all possible accident / incident types into account, then the basis for a robust SMS does not exist. To overcome these limitations, standard definitions for airport surface safety occurrences that will used in the rest of this thesis have been developed in this chapter.

Finally, this chapter highlighted the central role and importance of safety data across the four cornerstones of the SMS. The critical elements include accident / incident definitions, data collection techniques and methods of investigation and associated the quality of the collected data, as well as analytical data analysis methodologies and tools. The next chapter moves on to systematically review how state-of-the-art efforts for airport surface safety analysis and risk mitigation comply with these requirements.

5 Airport Safety Modelling

The previous chapter completed the contextual aspect of this thesis by introducing the fundamentals of safety and Safety Management Systems (SMS) and highlighting the requirements for the development of a robust SMS. This chapter systematically reviews the state-of-the-art of airport surface safety analysis and risk mitigation efforts and highlights the limitations of current approaches in respect to the SMS requirements established in the previous chapter. With this, this chapter addresses the third research objective.

The chapter starts with analysing how the process of surface operations can fail. To understand the current status of airport surface safety analysis and risk mitigation, a state-of-the-art-review is given in the following section. In addition, an initial taxonomy of causal factors that underlie failures in the process of surface operations is constructed based on the literature findings. Subsequently, the lack and need for an integrated approach is highlighted and requirements for a sophisticated airport surface safety analysis framework are developed.

5.1 Failure Modes of Airport Surface Operations

Chapter 3 has indicated that an omission of tasks within an operation of a stakeholder can challenge the safety of the system. The following section builds upon this and analyses where the process model (shown in Chapter 3, section 3.2.) can fail. Figure 43 shows the tasks of the airport authority and gives examples how each task can be challenged. Subsequently, Figure 44 shows an excerpt of the tasks of a pilot and highlights possible failures of the activities within a pilot's operation.

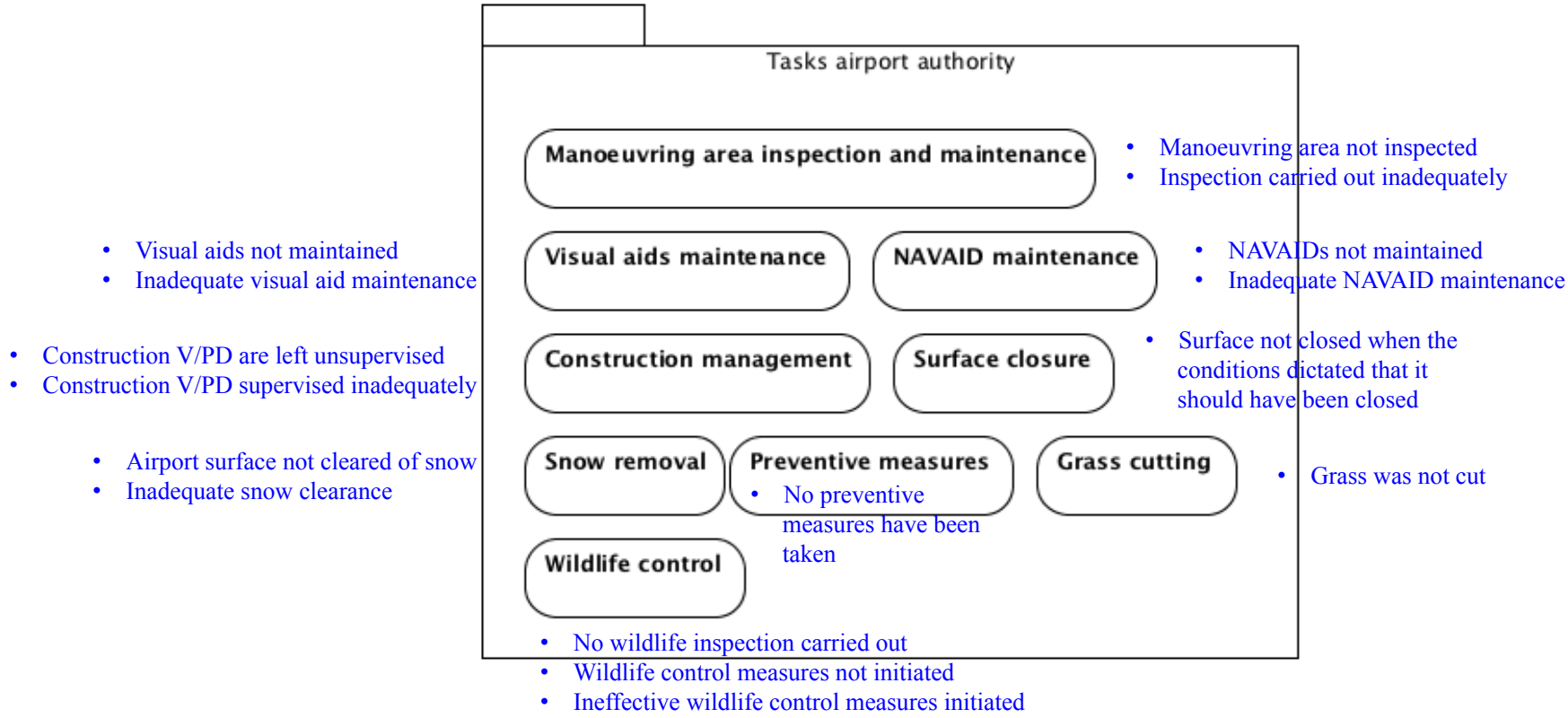


Figure 43: Potential process failures of the airport authority's operation

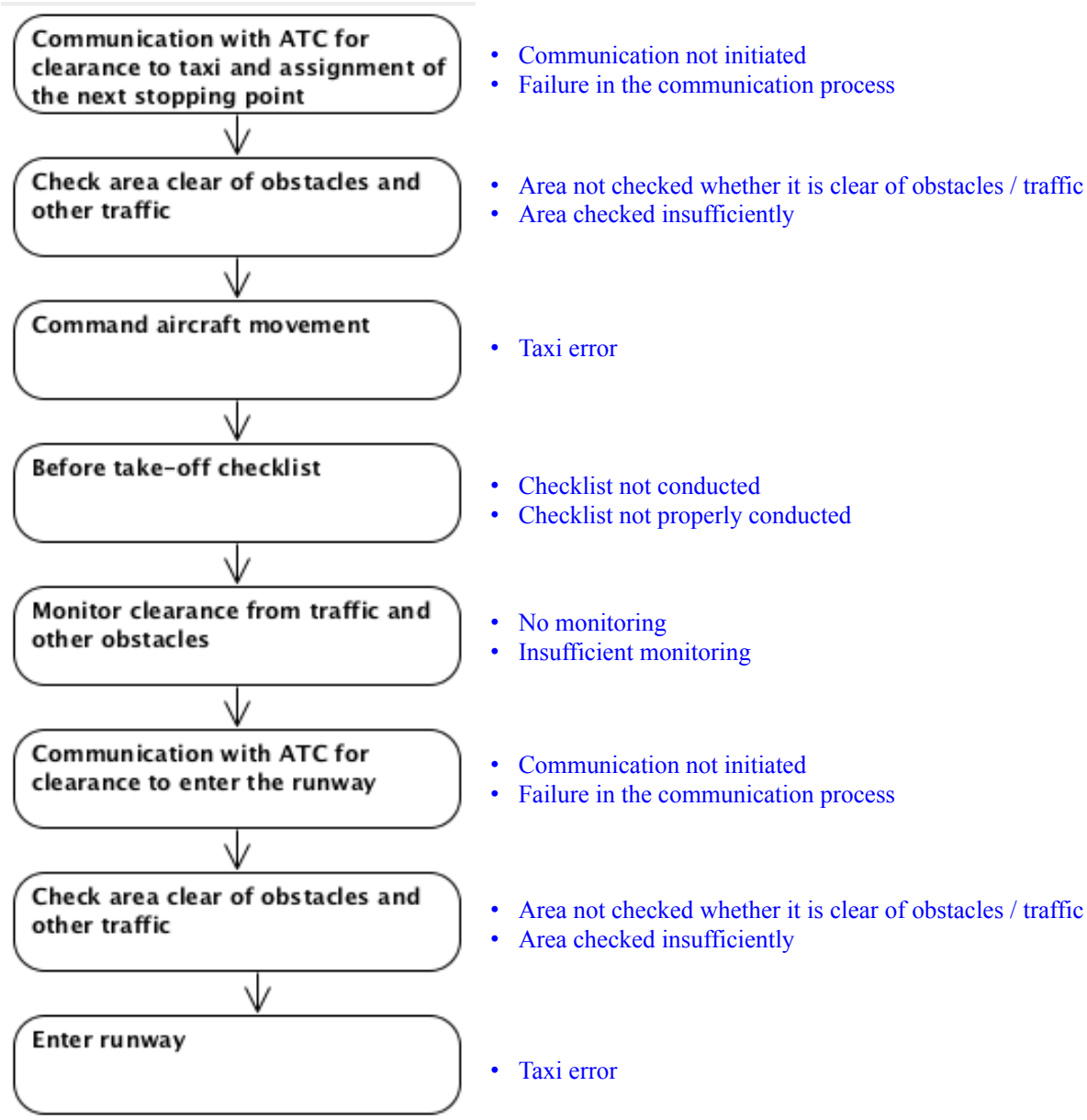


Figure 44: Potential process failures of the pilot's operation

As can be seen from Figures 43 and 44, each of the activities of both, the airport authority and the pilot, can fail in various ways. Similarly, each activity in the operation of a V/PD (section 3.2.5.2), ATC (section 3.2.6.2), and the regulator (section 3.2.7) can fail. In addition, each element of the airport surface infrastructure shown in section 3.2.2, Figure 12, can be subject to a technical failure.

Overall, it can be concluded that the process model can fail in all of it elements and, therefore, it is vital to understand the factors that can lead to a failure of the system. These factors are referred to as *causal factors* and the next section reviews the relevant literature to identify them.

5.2 Airport Surface Safety Modelling – State-of-the-Art

5.2.1 Method for Reviewing the Literature

At its core, safety risk management means identifying, analysing and mitigating the causes of occurrences, which are, according to the ICAO, defined as "actions, omissions, events, conditions, or a combination thereof, which lead to an accident or incident" (International Civil Aviation Organization, 2001c). The literature review, therefore, has three aims:

i) To review the literature on the causal factors that underlie airport surface accidents / incidents and to develop an initial list of these causal factors;
ii) To identify the deficiencies in the current state-of-the-art of airport surface safety analysis with reference to the SMS requirements defined in the previous chapter; and
iii) To identify risk mitigation efforts including technologies, training programs, procedures and recommendations for best practices.

The literature has been consolidated based upon the following factors:

- Chapter 4 has shown that all occurrence types are relevant and can have fatal consequences and, therefore, literature that captures all accident and incident types must be reviewed;
- Chapter 2 highlighted that airports differ in their characteristics across countries and for that reason a global review is aspired;
- Chapter 3 identified five main stakeholders (i.e. airport operator, pilots / airline, ATC, ground handling companies, regulators) involved in airport surface operations and consequently the review aims to reflect the perspectives of all these relevant stakeholders;
- As a substantial amount of literature and studies has been published in the area of airport surface safety, this review focuses on academic literature and major studies initiated by the industry.

A total of 65 studies have been analysed in detail and included in this review. Figure 45 contains the distribution of the analysed literature per occurrence type.

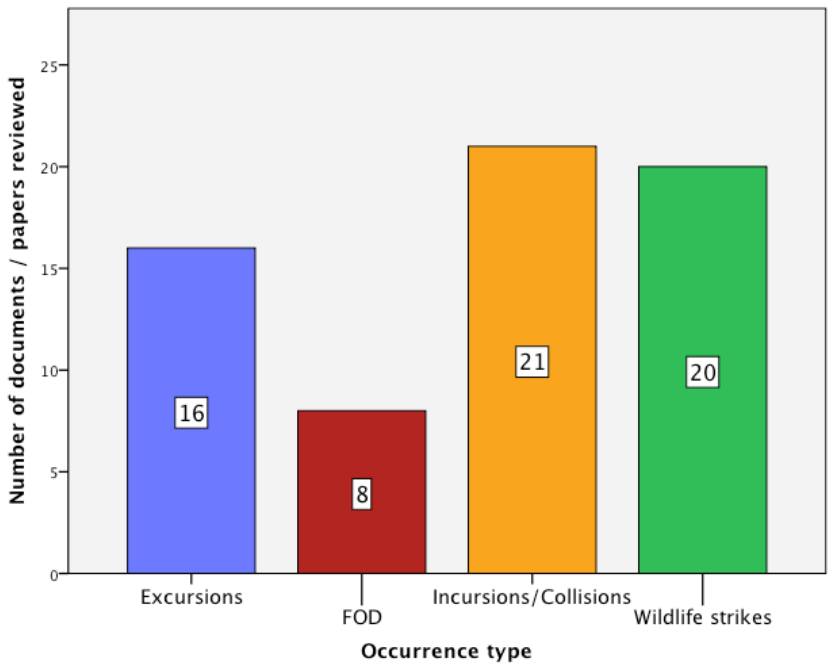


Figure 45: Distribution of literature per occurrence type

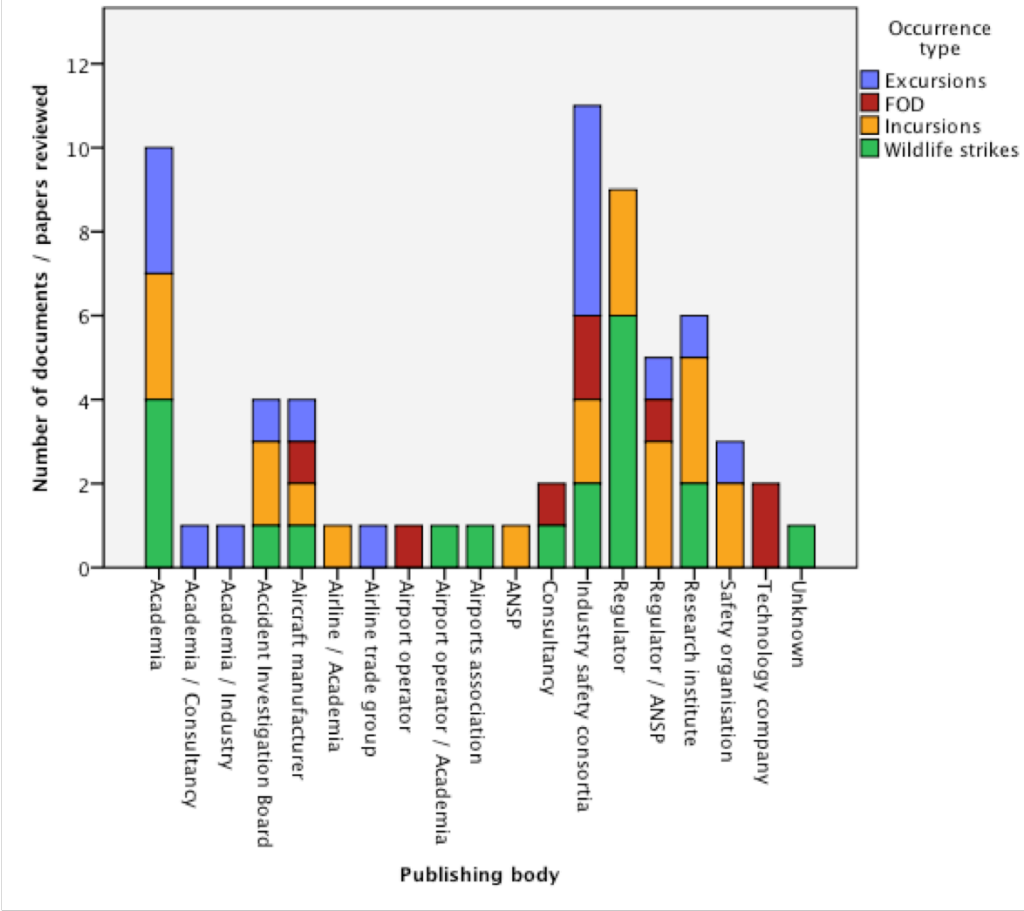


Figure 46: Publishing bodies

Whilst an extensive number of publications are available for the analysis and mitigation of incursions and wildlife strikes, there is little literature available for FOD occurrences and the majority of studies and research papers relating to excursions have only been published recently.

The literature included in this review has been sourced worldwide, with the details discussed in the following sections for each occurrence type individually. Figure 46 meanwhile, shows the large distribution of publishing bodies.

The literature consistently addresses single occurrence types. This structure is retained and thus the following sections review each accident / incident type individually. Based on the SMS requirements established in Chapter 4, the reviewed studies are evaluated in terms of:

- Scope (i.e. occurrence types that are addressed);
- Represented stakeholder perspective;
- Data sources and data quality;
- Analytical methodologies;
- Research outcomes; and
- Proposed risk mitigation measures.

In each part, the sample characteristics of the reviewed publications are introduced (in terms of scope and represented stakeholder perspective) and the causal factors summarised. Subsequently, a critical review of the analytical methodologies and a discussion of the underlying data sets and their quality are given. An assessment of the quality of safety data is essential for any analysis, but in particular, when attempting to aggregate databases across organisations. Three aspects of data quality need to be considered: external factors (i.e. how accurately does the database reflect occurrences), internal factors (i.e. how precise is the data), as well as the reporting level and the details of data quality assessments in aviation are discussed in Chapter 6.

In terms of analytical methodologies, three types have been identified in relation to the analysis of airport surface safety studies and Figure 47 summarises their characteristics. The safety studies can be categorised in i) review-only studies, ii) qualitative studies, and iii) quantitative studies and the reviewed literature will be benchmarked against these categories.

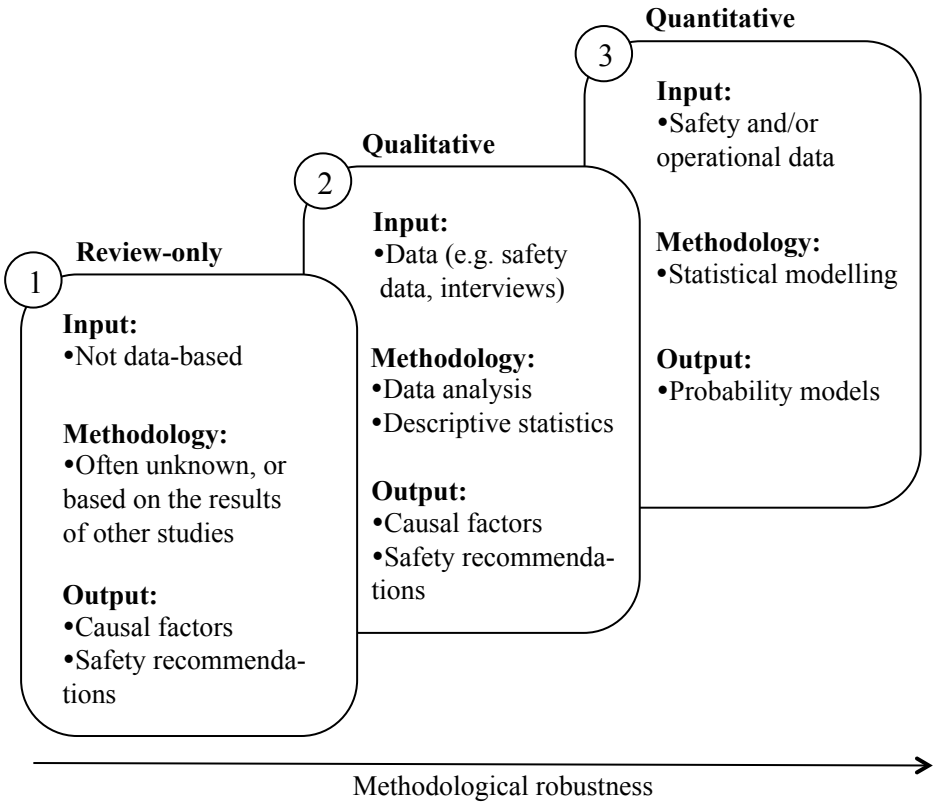


Figure 47: Analytical methodologies

The first type concerns studies that give an overview of the causal factors that underlie occurrences, and provide safety recommendations based upon these factors. These reports are purely qualitative and the causal factors are typically derived from the findings of the data analysis published in other papers / reports.

The second type of research involves the analysis of data from various sources (e.g. safety data, interviews). These studies extract causal factors from the collected data and use descriptive statistics (e.g. frequency analyses) to present the findings. Such studies result either in the identification of the causal factors or an outline of safety recommendations based upon the results.

The third type refers to quantitative approaches that go beyond descriptive statistics. In that respect, it is reviewed how existing studies address the quantification of the safety risk (as the product of probability and severity) and whether an acceptable level of safety (ALoS) at the State-level, or targets for a safety risk that is as low as reasonable practicable (ALARP) at the organisational level have been set. Based on the SMS requirements defined in the previous chapter, level 3 of the analytical methodologies is the most desirable category as SMS are data driven and require the quantification of safety risks.

In addition to the identification of causal factors and the review of analytical methodologies, risk mitigation strategies, as proposed in the literature, are outlined for each of the reviewed occurrence types. Finally, a review of existing taxonomies is given. There results of the review are consolidated into:

i) An initial taxonomy of causal factors that underlie all airport surface safety accidents and incidents; and

ii) An outline of the limitations of previous research and the requirements for future research.

Figure 48 summarises the methodology for the literature review.

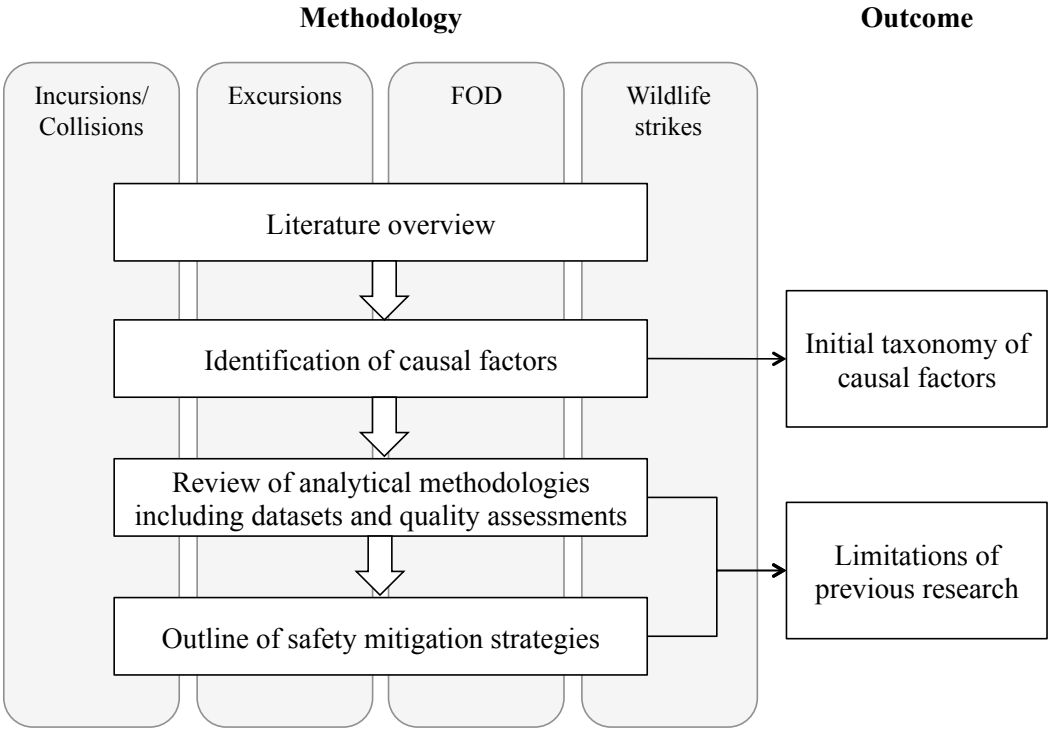


Figure 48: Methodology outline for literature review

5.2.2 Incursions / Ground Collisions

Incursions are precursors to ground collisions, which can lead at their extreme to substantial damage of aircraft and major loss of life. To prevent such accidents from happening, incursions have been the centre of attention in the aviation industry for over a decade. To identify the state-of-the-art of incursion analysis, modelling and prevention, a selection of 21 research papers and safety initiatives (selected according to the criteria introduced in section 5.2.1) have been reviewed, representing the main research efforts and industry initiatives for the prevention of incursions, and ground collisions, respectively.

The prevention of incursions has not only been addressed by the stakeholders directly involved in such incidents (e.g. airlines, ANSPs), but also by academia and research institutes. The relevant entities include aircraft manufacturers (Airbus, 2004c), airline representatives (Young and Vlek, 2009), ANSPs (Airservices Australia, 2002), regulators (Federal Aviation Administration, 2002, 2007c, 2008b, 2009c, 2010d; International Civil Aviation Organization, 2007; La Direction Générale de l'Aviation Civile, 2007; Transport Canada, 2000), accident investigation boards (Australian Transport Safety Bureau, 2004; National Transportation Safety Board, 1987), safety organisations (The European Organisation for the Safety of Air Navigation, 2008a; The European Organisation for the Safety of Air Navigation Experimental Centre, 2006), international safety consortia (Runway Incursion Joint Safety Analysis Team, 2000; Runway Incursion Joint Safety Implementation Team, 2002; The European Organisation for the Safety of Air Navigation, *et al.*, 2011), research institutes (e.g. NASA Ames (Hooey and Foyle, 2006), NLR (Stroeve*, et al.*, 2009, 2011), VOLPE (Biernbaum and Hagemann, 2012)), and academia (Chang and Wong, 2012; Kim and Yang, 2012; Rogerson and Lambert, 2012). In addition, there have been action plans at the local airport level (e.g. training and awareness campaigns (Zurich Airport Runway Safety Team, 2011)).

Most studies reviewed here considered incursions on runways, and the majority focused on the investigation of incursions that involved infringement of aircraft only. Just two studies have addressed incursions or collisions on the airfield (The European Organisation for the Safety of Air Navigation Experimental Centre, 2006; Young and Vlek, 2009). Since the introduction of the ICAO's runway incursion definition in April 2006, and its adoption by national authorities in the late 2000s (e.g. Federal Aviation Administration, 2009c; Goodman and Fraser, 2011) the definition of runway incursions has been harmonised. The underlying data are for the most part national datasets, with the

main body of the research coming from the U.S. Only two studies used global databases. Appendix II Table 1 provides an overview of the reviewed literature and summarises the underlying datasets, data quality issues, analytical methodologies and research outcomes. In addition, the advantages and disadvantages of each study / initiative are discussed.

5.2.2.1 Causal Factors

17 studies determined the factors that can cause incursions. These factors can be classified into eight groups, related to the initial process model of airport surface operations developed in the previous chapter. These include pilot, ATC, V/PD (including V/PD from ground handling companies, the airport operator, and others, e.g. construction workers), and regulatory factors, as well as causes that originate from the airport surface physical infrastructure and the environment (e.g. weather / visibility). In addition, most studies emphasised the central role of communication. Although communication-related factors can be attributed to each of the stakeholders, they are often described as a category on its own in the literature, and therefore, are treated as such here for the moment. Finally, it emerged that traffic characteristics, such as the traffic volume, play a role in the occurrence of incursions. For instance, Transport Canada (2000) identified that the likelihood of an incursions increases more rapidly when capacity-enhancing procedures are in effect. The identified causal factors are summarised in Table 17

Table 17: High-level causal factors for incursions

Causal factors	Airbus (2004c)	Airservices Australia (2002)	Australian Transport Safety Bureau (2004)	Biernbaum and Hagemann (2012)	Chang and Wong (2012)	Federal Aviation Administration (2002)	Federal Aviation Administration (2007c)	Hooey and Foyle (2006)	International Civil Aviation Organization (2007)	Kim and Yang (2012)	La Direction Générale de l'Aviation Civile (2007)	National Transportation Safety Board (1987)	Rogerson and Lambert (2012)	The European Organisation for the Safety of Air Navigation (2008)	The European Organisation for the Safety of Air Navigation Experimental Centre (2006)	Transport Canada (2000)	Young and Vlek (2009)
Communication	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	
Pilot	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓		✓	✓		
ATC	✓	✓	✓	✓			✓		✓	✓	✓	✓		✓	✓	✓	
V/PD									✓	✓	✓			✓			✓
Airport design / physical infrastructure	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Traffic				✓									✓	✓		✓	
Weather / visibility	✓			✓	✓		✓	✓					✓	✓	✓		
Regulator			✓		✓												

The pilot-related factors that can contribute to an incursion include: a lack of pilot situational awareness caused by distractions (e.g. flight deck not sterile, head down tasks, conversations in the cockpit) or the pilot forgetting e.g. clearances; airport-related factors such as unfamiliarity with the airport, or complacency; actions without clearance (e.g. entering a runway, crossing the hold line, taking off without clearance, taking off from the wrong runway or a taxiway); or communication-related errors that occur for instance during the communication process with ATC. In addition, inadequate team operations (e.g. improper cross-checking, inadequate supervision of the first officer by the pilot in command) and personal and / or competence-related factors such as pressure (e.g. not to lose a slot, by being already late), or inexperience are mentioned as causes frequently throughout the literature.

Similarly, common causal factors for ATC are a loss of situational awareness through distractions (e.g. through conversations in the tower, head-down time, a restricted view to the manoeuvring from the ATC tower) or ATC forgetting about things such as the position of an aircraft / VPD, the closure of a runway, or that a clearance has been issued. In addition, the issue of an incorrect or inadequate clearance, the misidentification of aircraft / V/PD positions, factors in relation to inadequate teamwork (e.g. inadequate controller handover, a controller covering more than one position, the absence of a supervisor in the tower), as well as competence and experience, are mentioned frequently in the literature. Finally, technical failures, such as the failure of the surveillance system (e.g. ground radar) are acknowledged contributors to incursions.

V/PD-related factors that can cause an incursion include, amongst others, a lack of situational awareness caused by distractions or unfamiliarity with the airport; inadequate training on the airfield and, associated with this, e.g., a lack of knowledge of airport signs and markings, or even the absence of any V/PD training. Furthermore, a non-compliance with ATC instructions, incorrect position reports to ATC, a failure to obtain ATC clearance at all, and the lack of proper communication between V/PD and ATC are each mentioned in the literature. Although V/PD account for 21.0% of runway incursions in the U.S. (Federal Aviation Administration, 2010d) and 29.0% in Europe (The European Organisation for the Safety of Air Navigation, 2011d), V/PD-related factors are only covered in five of the studies.

Failures in the communication process between stakeholders are emphasised by most of the reviewed publications. For pilots, these include the use of non-standard phraseology, poorly enunciated, heavily accented, and rapidly spoken language, read back errors (e.g.

incorrect or missing read back), and the misunderstanding of controller instructions. Similarly, incorrect read back and incorrect phraseology are mentioned as causes for incursions involving V/PD. In addition, vehicles that are not equipped with a radio and therefore are unable to establish contact with ATC are often involved in an incursion. Incorrect / inadequate instructions, the omission of one or more steps in the communication process, overlong and complex transmissions, and the use of languages other than English are cited failures in the communication process of ATC.

Besides human-related factors, the airport itself, its infrastructure and the maintenance associated with it, are also factors that can contribute to incursions. Thus, a complex manoeuvring area layout, inadequate marking, signage and lighting, and a non-normal airport configuration caused, for instance, through construction work (e.g. closed surfaces) can each contribute to the loss of situational awareness on the part of the stakeholders. Similarly, weather-related factors, and in particular visibility (e.g. low visibility conditions induced by haze, dust, light or heavy rain, the position of the sun in the pilot's eyes, snow / icing covering airport surface markings, night time operations, 'Sea of lights'), can hinder airport surface operations.

Finally, inadequate regulations were mentioned by two studies, and the contribution of the prevailing traffic (e.g. (hourly) traffic volume, hourly runway entries, percentage of GA operations, traffic mix) at an airport was acknowledged by four studies as shown in Table 17.

The factors mentioned in an early study by the National Transportation Safety Board (1987) (e.g. communication problems, inadequate markings and signage, ATC forgetting about aircrafts / V/PD or the closure of a runway) are still valid today. Overall, the causal factors mentioned most frequently in the literature are pilot, ATC and communication-related factors. Although the interaction of the factors is indicated (e.g. a failure in the communication process between pilot and ATC), none of the studies has analysed this aspect further to show how the factors interact with each other and which are the most frequent interactions. Since most of the studies use national data sets the causal factors are typically presented for individual countries. Only the Australian Transport Safety Bureau (2004) compares its analysis of Australian runway incursions more widely to Europe and U.S. This comparison is limited, however, to trends (i.e. incursion rates) and does not cover a geographical comparison of causal factors. Since the majority of studies focus on runway-related occurrences, it is also not possible to compare whether the same factors underlie incursions on runways and taxiways.

5.2.2.2 Analytical Methodologies and Data Quality Issues

Figure 47 introduced possible analytical methodologies for the analysis of airport surface safety occurrences (i.e. review-only, qualitative, quantitative) and all three types of studies have been identified in relation to the analysis of incursions.

First, qualitative studies that derive causal factors from the findings of data analyses published in other papers / reports were identified (e.g. Airbus, 2004c; International Civil Aviation Organization, 2007; The European Organisation for the Safety of Air Navigation, *et al.*, 2011).

Second, the review identified a number of studies that analyse data from various sources, including safety data (Australian Transport Safety Bureau, 2004; La Direction Générale de l'Aviation Civile, 2007; Young and Vlek, 2009), interviews (National Transportation Safety Board, 1987), site visits (Federal Aviation Administration, 2002; Transport Canada, 2000), and surveys of SMEs (Airservices Australia, 2002). These studies extract causal factors from the collected data and use descriptive statistics (e.g. frequency analyses) to present the findings. Such studies result either in the identification of the causal factors (Airservices Australia, 2002; Australian Transport Safety Bureau, 2004; La Direction Générale de l'Aviation Civile, 2007), or an outline of safety recommendations based upon the results (Federal Aviation Administration, 2002, 2007c, 2008b, 2009c, 2010d; National Transportation Safety Board, 1987; Transport Canada, 2000; Young and Vlek, 2009). Although various methods for data collection are used in previous research, only the Runway Incursion Joint Safety Analysis Team (2000), the National Transportation Safety Board (1987) and Transport Canada (2000) combine some of the methods. The combination of research methods allows more detailed insight to be attained into the causal factors and to understand more clearly ill-defined areas that may not have been captured very well through the primary method of data collection.

The majority of studies fail to specify how the causal factors have been extracted from the data. Possible methods include grounded theory, whereby a theory is developed newly from data (Glaser and Strauss, 2009), template analysis that uses an initial template which is refined over time (Symon and Cassell, 1998), or data coding according to an existing taxonomy.

Finally, the review identified five quantitative approaches that go beyond descriptive statistics. EUROCONTROL's Integrated Risk Picture (IRP) quantifies the risk for five accident scenarios to which ATM can make a significant contribution with the aim to

identify safety priorities for ATM. Fault trees are developed for each accident scenario, including runway collisions and taxiway collisions, and these are quantified using worldwide accident data. The risk of each specified accident category is quantified by providing a structured breakdown of their causes together with their probability of occurrence. In addition, common causal factors that affect all accident scenarios are separately presented in an influence model (The European Organisation for the Safety of Air Navigation Experimental Centre, 2006). IRP is limited by modelling mainly the contribution of ATC and ATM to accidents. In the context of runway and taxiway collisions, this means that IRP does not model pilot or airport-related factors in detail. Collisions with V/PD on the airport surface are missing entirely. Fault Tree analysis has also been applied by Kim and Yang (2012) to model the contribution of hazards to runway incursions, and to identify those hazards that are most critical in terms of their failure probability. A disadvantage of Fault Trees is that failure probabilities can only be modelled for defined scenarios and are therefore, difficult to establish for complex systems, such as airport surface operations, which require the interaction of various actors.

Another method to prioritise causal factors is the Analytical Hierarchy Process (AHP), which has been applied in three of the studies. AHP is a structured technique based on expert judgments that derives priorities from a series of pairwise comparisons of factors. The factors to be compared can be derived from the literature (Chang and Wong, 2012; Kim and Yang, 2012) or can be based on SME opinions (Rogerson and Lambert, 2012). Since the pairwise comparisons are done by SMEs, the AHP is reliant on the expertise of the SMEs and their judgement.

AHP prioritises causal factors and the results can be used to channel risk mitigation measures. The reverse approach to prioritising the causes is to prioritise the consequences, i.e. occurrences. Through the application of regression models the causal factors that underlie the most undesired occurrence types can be modelled. For example, a recent study by Biernbaum and Hagemann (2012) models the impact of contextual factors on runway incursion severity using logistic regression models. The authors model the relationship between aircraft (e.g. phase of flight, number of aircraft involved), pilot (e.g. foreign pilot, pilot hours in make and model), airport (e.g. number of runway intersections, hotspots), radar (e.g. presence of airport surface detection equipment (ASDE), ATC (e.g. age, time on shift), weather (e.g. temperature, visibility), and other factors (e.g. day vs. night time operations) and four runway incursion severity levels. Whilst Biernbaum and Hagemann, (2012) provide an extensive overview of the factors that contribute to runway incursions,

the study focuses on the investigation of contextual factors, i.e. conditions that have been present during the occurrence of a runway incursion, but does not consider the causes of the incidents. Modelling the relationship between the causes (which can be extracted from occurrence reports) and severity would allow those factors that are most critical for the occurrence of high-severity incidents to be identified and addressed. The study is limited, however, in that it models only runway-related incursions and neglects V/PD operations (i.e. only pilot and ATC-related factors are considered).

A practical tool to be used for runway incursion risk assessments was developed by the European Organisation for the Safety of Air Navigation (2008). The Aerodrome Runway Incursion Assessment (ARIA) tool was developed with the objective of providing a simple and easy-to-use computer-based assessment that would facilitate a Local Runway Safety Team to identify the possibility of runway incursions occurring at their airport. ARIA provides a risk index for each airport that reflects the probability of having a runway incursion. The tool takes contributory factors (e.g. partially blocked line of sight from the ATC tower, tower staffing problems) as well as runway incursion reduction factors (e.g. continued stop bar usage at all runway entries) into account and weights these factors based upon historical safety data and SME judgment. The overall risk index is calculated through an additive model, however, the appropriateness of such a model for the aggregation of factors and possible alternatives are not discussed. Overall, however, the considered risk factors and countermeasures offer a good awareness tool for airports.

Finally, Stroeve*, et al.* (2009) developed a collision risk model for a specific runway incursion scenario, in which an aircraft taxies towards the crossing of an active runway while its crew has inappropriate situational awareness. Using Monte Carlo simulations an assessment of the risk of a collision between the aircraft taxiing with an aircraft taking-off is presented by event probabilities. Stroeve, *et al.* (2009) provide a systematic approach for accident assessments that describes the performance of a system as a whole and takes the interactions between multiple agents (i.e. humans and technical systems) into account. The disadvantage of their model is that it is computationally intensive and the modelling of a very specific runway incursion scenario does not allow for a holistic risk assessment of airport surface operations.

In summary, the depth of the methodologies used for the analysis and modelling of runway incursions varies significantly from simple causal factors analysis and descriptive statistics to the modelling of accident / incident scenarios. Although the quantitative studies claim to model the ’risk’ of incursions, they have predominantly addressed the

probability of occurrence (i.e. of having an incursion). Only one study attempted to model their severity, but addressed only contextual factors and failed to model the relationship between the causes of incursions and their severity. Safety targets in form of an ALoS or ALARP have not been proposed based on these calculations.

Among the reviewed literature 13 studies are based upon the analysis of safety data, however, only four of them mention data quality. Biernbaum and Hagemann (2012), La Direction Générale de l'Aviation Civile (2007), and the Runway Incursion Joint Safety Analysis Team (2000) describe the limitations of their data, but the discussions are limited to the internal quality of the databases (e.g. missing cells). Also, Transport Canada (2000) assessed the quality of its data sources and evaluated them as reliable. However, this statement is not supported by any further explanations as to how the data was assessed and the reliability defined. Overall, data quality is rarely addressed, and if it is, then it is limited to internal data quality issues (i.e. precision). None of the studies evaluated the accuracy of the data (i.e. whether the data reflects the truth of what happened), even though it is important that this should be discussed when dealing with safety data, and in particular, when analysing occurrence reports for causal factors. A detailed overview of the reviewed studies, their underlying data sets, data quality issues, analytical methodologies and research outcomes is given in Appendix II Table 1.

5.2.2.3 Safety Risk Mitigation Strategies

The industry has initiated many safety programmes and awareness campaigns to address incursion. These are initiated at various levels, ranging from awareness campaigns at an organisational level (e.g. airport, airline) to safety programmes established by regulatory bodies. Initiatives at the local level include the establishment of Runway Safety Action Teams (RSAT); these teams consist of representatives of the relevant stakeholders (e.g. airport, airlines, ATC, regulator) and discuss surface operations and safety concerns in order to develop action plans (Federal Aviation Administration, 2011d).

Besides general awareness campaigns, the analysis of causal factors typically leads to more targeted recommendations for mitigation measures, best practices, training programmes, and guidelines for the prevention of incursions. To reduce runway incursions, the industry has also worked on the development of technologies that help to improve

situational awareness. These include improved surveillance to support ATC, as well as ground-based and on-board pilot / V/PD notification equipment. Currently, the Airport Surface Detection Equipment – Model 3 (ASDE-3) and the Airport Surface Detection Equipment – Model X (ASDE-X) are employed to improve situational awareness for ATC.

ASDE-3 provides radar surveillance of aircraft and vehicles (Airbus, 2004c). The succeeding version, Model X, provides high-resolution surveillance information under all weather and visibility conditions. Model X is more sophisticated than ASDE-3 and is able to integrate data from a variety of sources, including aircraft transponders and multilateration sensors. ASDE-X creates a continuously updated map of all airport surface operations which ATC can use to monitor the ground traffic (Federal Aviation Administration, 2010f). In addition, the Airport Movement Area Safety System (AMASS), an add-on enhancement to the ASDE-3 radar, provides ATC with aural and visual warnings of potential collision risks (Airbus, 2004c). Similarly, the ASDE-X Safety Logic (AXSL) uses surveillance information from ASDE-X to determine if current or projected positions and movements of aircraft and vehicles present a potential collision situation. ASDE-3 / AMASS has been used at major U.S. airports while the new system, ASDE-X, has been implemented at 35 U.S. airports (Federal Aviation Administration, 2010f).

In Europe, the Advanced Surface Movement Guidance and Control System (A-SMGCS) is currently under development and aims to assist ATC by providing four functions. Surveillance through display systems showing the position of aircraft and vehicles on the ground to ATC forms the core of the system. Building on that, the control function provides conflict detection and alerts regarding situations in the movement area that could potentially compromise safety. A routing function ensures that the most effective route is designated for each aircraft and vehicle, and a guidance function gives indications of the assigned route to pilots and vehicle drivers. The fully developed A-SMGCS will combine facility-based ATC notification equipment with ground-based and on-board pilot / V/PD notification equipment. Currently, major European airports are in the process of implementing the basic surveillance and control functions. The routing and guidance functions are the subject of further research and development (The European Organisation for the Safety of Air Navigation, 2010b). Moving Map Displays (air navigation devices that display the aircraft's position on moving film of an aeronautical chart) are capable of assisting the guidance function by indicating the course and distance to the destination (Jeppesen, 2013).

To improve situational awareness in the manoeuvring area, Runway Status Lights (RWSL), and the Final Approach Runway Occupancy Signal (FAROS) have also been developed and tested. RWSL identifies any possible conflict with other surface traffic and warn pilots when it is unsafe to cross, enter, or begin take-off on a runway via a series of red lights embedded in the pavement. FAROS is a technology that provides pilots on final approach notification that their identified runway for landing is occupied and uses the concept of protected zones on the runway and entrance taxiways. The zones are defined by a series of embedded inductive loops at entrance and exit points of the zones. As an aircraft or vehicle enters or leaves a zone, the magnetic field around the loops is disturbed, thus indicating its presence. FAROS uses the Precision Approach Path Indicator (PAPI) lights to give direct notification to the pilots, through a flashing of the lights, that the runway is occupied and unsafe for landing (Federal Aviation Administration, 2008b). A good review on existing runway incursion avoidance technologies and alerting systems is given by Schonefeld and Moller (2012).

The main conclusions from the analysis of incursion literature and safety initiatives are summarised as follows:

- The research is initiated by industry as well as research institutes and academia;
- The scope of this research is limited (i.e. consideration of only runway incursions and focus on aircraft-related incursions);
- A variety of data collection methods have been identified in the literature but are often used in isolation;
- Most research fails to specify the methodology of how the causal factors have been extracted from safety data;
- Causal factor analyses are predominantly of a qualitative nature with only a few studies trying to model the factors;
- Previous research has focused on modelling the probability of the occurrence of incursions or the probability of the occurrence of causal factors leading to incursions. A robust approach to modelling the severity of incursions based upon their causes is missing;
- Data quality is rarely addressed and if so, only its internal aspects. None of the studies has questioned the external validity of the data, analysed the reporting levels, or assessed whether it is valid to aggregate multi-national data sets;

- A few studies use safety data from a variety of databases and therefore data with potentially differing qualities may have been aggregated;
- Studies typically reflect the perspective of individual stakeholders (e.g. analysis of only regulatory data), and approaches that combine the complementary views of the relevant stakeholders do not exist;

The review identified that incursions have been a 'hot topic' in the industry over the last decade. Therefore, it is surprising that a robust multi-stakeholder approach that takes the complementary viewpoints of all the relevant stakeholders into account has not yet been proposed.

To overcome the limitations outlined above, this thesis addresses airport surface safety in a holistic manner by considering all occurrence types, both, on runways and taxiways, and from the perspective of all relevant stakeholders. A robust methodology that will be outlined at the end of this chapter in section 5.3 ensures the reliability and validity of the work. The framework for a holistic airport safety management requires the use of standard definitions (developed in Chapter 4) and the collection of a reference data set that fulfils the requirements of an integrated approach (Chapter 6). The data must be assessed in terms of internal validity, external validity and reporting levels in order to determine whether multi-national safety data can be aggregated (Chapter 6). To provide a standard tool for data coding and analysis, a taxonomy of causal factors applicable to all stakeholders is developed (Chapter 9). In addition, a systematic analysis framework to model the functional relationship between the severity of airport surface accidents and incidents and their underlying causal factors is proposed (Chapter 11). To achieve triangulation, a combination of both, qualitative and quantitative research methods, is used throughout this thesis.

5.2.3 Excursions

Whilst incursions have been in the spotlight for over a decade, the importance of excursions and their prevention has only recently received attention from industry and academia.

A total of 16 major research studies and industry campaigns that address excursions and their prevention have been identified and reviewed. The literature emanates from a number of entities including aircraft manufacturers (Airbus, 2004b), accident investigation

boards (Australian Transport Safety Bureau, 2008b, 2009), regulators (Federal Aviation Administration, 2007a), international safety consortia (Flight Safety Foundation, 2000, 2009; International Civil Aviation Organization / International Air Transport Association, 2011; The European Organisation for the Safety of Air Navigation, 2010d; The European Organisation for the Safety of Air Navigation, *et al*, 2013; The European Organisation for the Safety of Air Navigation SKYbrary, 2012b), an airline trade group (International Air Transport Association, 2011), research institutes (Es, 2005; Es*, et al.*, 2009; Hall*, et al.*, 2008), and academia (Ale*, et al.*, 2009; Ju, 2011; Valdés*, et al.*, 2011; Ziegler, 2012).

There have been no studies published by those stakeholders directly involved in surface operations (e.g. airlines, ANSPs, airport operators). These parties appear only as members of safety consortia (Flight Safety Foundation, 2009; The European Organisation for the Safety of Air Navigation, *et al.*, 2013). Overall, the majority of studies are initiated by accident investigation boards, safety consortia and academia. In contrast to incursions, excursions are rare events with some 417 worldwide accidents involving commercial transport aircraft during the 14-year period from 1995 to 2008 (Flight Safety Foundation, 2009) compared to 951 runway incursions in the fiscal year (FY) 2009 alone in the U.S. (Federal Aviation Administration, 2010d). As a consequence, stakeholders directly involved in surface operations may prioritise other problems such as incursions or wildlife strikes.

Although the split of attention is understandable given the various stakeholder responsibilities and resource constraints, structured communications with the safety investigators of a major European ANSP have revealed the potential dangers inherent in this practice. Experts pointed out that their organisation had focused so much on the prevention of incursions that they now experience more excursions (Structured communication with Safety Investigatiors Avinor AS ANSP, June 2011).

All the reviewed studies considered runway-related occurrences alone with none taking excursions on taxiways into account. In addition, the studies only analysed accidents, and sometimes serious incidents, rather than incidents more generally. Often, analyses focused on specific types of excursions and flight phases, such as runway overruns that occurred during landing. Only two studies considered all three types of runway excursions (i.e. overruns, undershoots and veer-offs). Overall, the scope of the studies varies and terminology is often not well defined. These findings reinforce the conclusions drawn from the review of airport surface safety occurrence definitions. In addition, the literature contains studies on approach and landing accidents that, as well as excursions, also include

controlled flight into terrain (CFIT) accidents and various incidents related to the approach and landing phases of flight (e.g. altitude deviations). Such studies (e.g. Morrison*, et al.*, 1993) have been excluded from the assessment, unless the causal factors for excursions and their impacts have been specifically addressed (e.g. as in Ale*, et al.*, 2009; Flight Safety Foundation, 2000).

Although the research originates mainly from North America, Europe and Oceania, most studies use databases that capture worldwide accidents. Appendix II Table 2 summarises the data sets, data quality, analytical methodologies and findings of the reviewed studies on excursions, and discusses their advantages and disadvantages.

5.2.3.1 Causal Factors

A total of 11 studies outline the causal factors that underlie excursions with the majority of these coming from within the industry. Research papers from academia are less concerned with the analysis of causal factors and tend to focus more on probability modelling, as discussed in the next section. The causal factors are classified into nine groups as outlined in Table 18.

Aircraft technical failures include, e.g., degraded engine performance and engine failure, damaged landing gears, tire failures, failure of the brakes or the anti-skid system, or problems associated with the thrust reverser and asymmetric thrust. Aircraft technical failures were mentioned by all studies apart from one that focused on the human-related aspects involved in excursions. Handling and maintenance failures are also associated with technical factors, although these are only mentioned in one document.

Besides aircraft technical failures, the main contributors to excursions are humans. The most prominent pilot-related factors involved in excursions during the landing phase of flight include, amongst others: an unstable approach, go around not conducted / considered, an approach path / glide slope deviation, and inadequate pilot technique during landing and touch down (e.g. too high, too fast, bouncing, hard, long, short, off-centre). No rotation because the rotation speed V_R is not reached, a premature rotation (before V_R), or the loss of directional control are often associated with excursions during the take-off phase of flight. In addition, aircraft weight calculation errors, or personal factors such as fatigue or stress can contribute to the occurrence of an excursion. Pilot-related factors are widely recognised and have been mentioned to various degrees in all of the 11 studies. The

impact of airlines, e.g. through the provision of inadequate procedures, has been acknowledged twice.

In addition to pilots, ATC can also contribute to the occurrence of excursions. ATC human-related factors include for instance an instruction to reject the take-off at a speed greater than the decision speed V_1, which is the maximum speed at which a rejected take-off can be initiated in the event of an emergency (Airbus, 2004b), a failure to descend the aircraft appropriately for the approach, a failure to allow the aircraft to fly at the appropriate control speed, or the selection of an inappropriate runway for the prevailing wind and / or runway surface conditions. Although ATC can have a significant impact on the occurrence of excursions, it was only mentioned in three studies.

On the other hand, the influence of weather and the environment is widely acknowledged in the literature. Weather-related factors include crosswinds, tailwinds, and other winds, turbulence, snow, ice, slush, and resultant contaminated runways, as well as (freezing) rain and aquaplaning. Furthermore, wildlife is an environmental factor that can lead to the excursion of an aircraft when a strike occurs.

Closely associated to the weather and environment are airport-related factors, such as the failure to provide timely or accurate runway condition information, an inadequate snow and ice control plan, or the non-closure of a runway when the conditions dictate. The inadequate clearance of runways that are contaminated (e.g. with FOD, oil, rubber), or of construction areas, can also be found as causal factors in the literature. Furthermore, airport design factors and infrastructure-related factors, such as a downward sloping runway, incorrect or obscured runway markings, and inadequate runway safety areas are mentioned in the literature. The majority of the reviewed studies acknowledge the impact of airports.

Aircraft manufacturers can also contribute to the occurrence of excursions, for instance through not providing operators with appropriate operational and performance information covering the spectrum of runway conditions they might experience.

Finally, the lack of a regulatory requirement to provide pilots with a consistent format for take-off and landing data for all runway conditions was quoted twice. Overall, the factors mentioned most frequently in the literature are thrust asymmetry, go-around not conducted, late or inaccurate runway condition reports, and wind shear.

Although almost all studies are based upon an analysis of worldwide excursion data, the causal factors are generally presented at an aggregate level. Whilst some studies show worldwide excursion trends (e.g. frequency of occurrence) (International Air Transport

Association, 2011; The European Organisation for the Safety of Air Navigation, 2010d), the causal factors are not compared across different regions. In addition, occurrences are often caused by more than one factor. Only the Flight Safety Foundation analysed factor interactions, but did not go beyond descriptive statistics, as discussed in the next section (Flight Safety Foundation, 2009).

Table 18: High-level causal factors for excursions

Causal factors	Airbus (2004b)	Ale, *et al.* (2009)	Australian Transport Safety Bureau (2008b, 2009)	Federal Aviation Administration (2007a)	Flight Safety Foundation (2000)	Flight Safety Foundation (2009)	Hall, *et al.* (2008)	International Air Transport Association (2011)	The European Organisation for the Safety of Air Navigation (2010d)	The European Organisation for the Safety of Air Navigation SKYbrary (2012b)	Valdés, *et al.* (2011)
Aircraft technical failure	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Handling / maintenance		✓									✓
Pilot human-related factors	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Airline (e.g. procedures)	✓						✓				✓
ATC human-related factors					✓	✓					✓
Environment / weather	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Airport	✓		✓		✓	✓		✓		✓	✓
Aircraft manufacturer		✓				✓					✓
Regulations						✓					

5.2.3.2 Analytical Methodologies and Data Quality Issues

Similar to incursions, the three types of analytical methodologies have also been identified for excursions. The first type of studies gives an overview of the causal factors that underlie excursions, and provides safety recommendations based upon these factors. These reports are purely qualitative and the causal factors are typically derived from the findings of data analyses published in other papers / reports (Airbus, 2004b; International Civil Aviation Organization / International Air Transport Association, 2011; The European Organisation for the Safety of Air Navigation, *et al.*, 2013). In some cases, however, the source of information is not specified at all (Federal Aviation Administration, 2007a; The European Organisation for the Safety of Air Navigation SKYbrary, 2012b).

The second type of research involves the analysis of safety data. These studies extract causal factors from occurrence reports and use descriptive statistics (e.g. frequency analyses) to summarise the factors. Such studies result either in the identification of the causal factors (International Air Transport Association, 2011), or an outline of safety recommendations based upon the results (Australian Transport Safety Bureau, 2008b, 2009; Flight Safety Foundation, 2000, 2009). The quantification of the relationship between excursions and their underlying causal factors through statistical modelling is missing in the literature. The use of regression models, for instance, could identify those factors that are most critical to the occurrence of excursions and thus could guide safety risk mitigation efforts more effectively.

As seen before, the majority of studies fail to specify how the causal factors have been extracted from the safety data. Three studies coded the safety data by means of existing taxonomies but, failed to discuss and demonstrate the appropriateness of the chosen taxonomies (Australian Transport Safety Bureau, 2008b; Khatwa and Helmreich, 1999; The European Organisation for the Safety of Air Navigation, 2010d). One study summarised their findings in a new taxonomy of causal factors for approach and landing incidents (Khatwa and Helmreich and 1999).

Finally, the review identified six quantitative studies that go beyond descriptive statistics to develop models to be applied for the risk assessment of excursions. Two of these studies developed risk ratios that represent the relative risk an aircraft operator has compared to a reference condition in which all risk factors are absent, e.g. the risk of

having an overrun when significant tailwind is present (Es, 2005; Es*, et al.*, 2009; The European Organisation for the Safety of Air Navigation, 2010d). Based upon this assessment, the European Organisation for the Safety of Air Navigation (2010d) provides recommendations for the mitigation of the identified risk factors. The second study however, stops with the assessment of the risk involved in runway overruns during the landing phase of flight.

Two further studies used regression analysis with the aim of modelling the probability, location and consequences of excursions (Hall*, et al.*, 2008; Valdés*, et al.*, 2011). The models are proposed to be used for the risk assessment of runway safety areas but are limited in their underlying assumptions. For instance, Hall*, et al.* (2008) model the wreckage location in the proximity of the runway threshold. Their model assumes that aircraft touch down on the threshold. However, the threshold is normally located at the extremity of a runway and aircraft touch down on the aiming points in the touchdown zone. Aiming points are located 150 – 400 m from the threshold depending on the length of the runway and landing distance available (International Civil Aviation Organization, 2004b).

To support aviation risk assessments a causal model for air transport safety (CATS) has been developed by Ale*, et al.* (2009). CATS contains detailed event chains for seven accident types and 33 scenarios, of which 16 can result in a runway excursion. The aim of CATS is to quantify the risk of all possible aviation accidents and to understand their causes in order to support the decision making process of aviation stakeholders. The final CATS product consists of a number of models and includes Event Sequence Diagrams (ESD), Fault Trees (FTs), and Bayesian Belief Networks (BBN). The models are quantified using mainly ADREP accident data and SME judgments.

CATS shows the sequences of events that lead to accidents, quantifies the probability of failure for each event in the sequence, and finally gives the probability of an accident occurring for each of the 33 scenarios. While the model contains detailed event chains for excursion scenarios, these are limited to pilot, aircraft technical failures, and weather and environmental factors and ignore the influence of, e.g., the airport operator and ATC. Similarly, one scenario models the probability of a collision on the runway by taking only pilot and ATC factors into account, neglecting the influence of V/PD or airport design factors. Overall, CATS has been developed from a flight perspective rather than a wider air traffic system perspective. In addition, the failure probabilities are to a large extent based on SME judgments due to a lack of safety data. The scenario-based development means

that accident probabilities are only valid for each scenario, i.e. CATS contains 16 probabilities to experience an excursion.

Finally, the study of Ju (2011) used a fuzzy analytical network process (ANP) to model the key risk factors involved in excursions. However, the results are questionable given the very poor description of the methodology used.

In summary, scientific papers and reports published by academia and research institutes use predominantly quantitative methods, which are more robust than purely qualitative approaches. Their findings are proposed to be of use for the assessment of the risk from excursions. The safety risk is defined as the product of probability and severity and previous research has once again focused on modelling the probability of excursions and neglected the modelling of their severity based upon their causes. On the other hand, industry studies are limited to purely qualitative research methods. These studies typically identify the causal factors that underlie excursions and translate the results into safety mitigation recommendations. A combined approach of qualitative analysis of causal factors and robust quantitative modelling of the causes is desirable in order to identify those factors that are most critical for the occurrence of excursions.

The sources of data used in the reviewed studies are in the majority of cases from accident investigation boards (e.g. ATSB, NTSB), or worldwide accident summary databases (e.g. World Aircraft Accident Summary (WAAS), National Aerospace Laboratory of the Netherlands (NLR) Air Safety Database). These data sources capture accidents and serious incidents. The investigation of accidents and serious incidents is regulated in ICAO Annex 13 (International Civil Aviation Organization, 2001c) and therefore, these occurrences should have been investigated to a common global standard. However, national variations may still exist and none of the studies addresses data quality issues that emerge from the aggregation of multinational safety data. Although restricted to the internal quality of the database (e.g. missing information), only Hall*, et al.* (2008) discuss the limitations of their data. Overall, the research to date on excursions does not address data quality issues.

In addition, the use of data from accident investigation bodies and databases for worldwide accidents means that incidents are not considered. Excursion incidents may be captured in the safety databases of the stakeholders directly involved in surface operations (e.g. airlines, or airports) but the current research fails to take such data into account.

5.2.3.3 Safety Risk Mitigation Strategies

Safety mitigation strategies for excursions include preventive risk controls and recovery risk controls. Preventive risk controls include technological solutions, and recommendations for the different aviation stakeholders based upon the identification of causal factors. In addition, training programmes and awareness tools and campaigns are offered as preventive measures.

Technical solutions include on-board equipment, such as Airbus' Runway Overrun Warning (ROW) and Runway Overrun Prevention (ROP) system. ROW / ROP on-board the new A380. ROW uses aircraft and airport data to compare, during the final approach, the required and actual available landing distance and triggers warnings when runways are too short for the aircraft. ROP is a protection system that is activated once the aircraft is on the runway. It computes the remaining stopping distance and automatically applies the maximum breaking power and reverse thrust required to avoid overruns (Airbus, 2009). ROW / ROP assist pilots during the approach and landing phase and helps to prevent pilot-related errors. Similarly, Boeing has recognised the impact of human-related factors and offers a landing distance calculator on electronic flight bags (Boeing Commercial Airplanes, 2012b). Honeywell has designed a SmartLanding^{TM} system that helps to reduce the risk of a runway excursion by providing timely alerts to crew members when the aircraft is approaching the runway too high, too fast or is not configured properly (Honeywell International Inc., 2013).

Recommendations derived from the analysis of causal factors fall into two classes: general and specific. The former include, for example, the initiation of local runway safety awareness campaigns. Specifics include those for:

- Airport operators (e.g. timely assessment of runway contamination during changing runway conditions, clear marking and signage of holding points),
- ANSPs (e.g. to ensure that the importance of a stabilised approach and final approach procedures is included in training and briefings for ATC),
- Aircraft operators (e.g. to include and monitor aircraft parameters related to potential runway excursions in their Flight Data Monitoring (FDM) program),
- Aircraft manufacturers (e.g. to present take-off and landing performance information in similar (common and shared) terminology and to agreed standards), and

- Regulators (e.g. to confirm that all infrastructure, practices and procedures relating to runway operations are in compliance with ICAO provisions) (The European Organisation for the Safety of Air Navigation, *et al.*, 2013).

In addition, various awareness materials and tools are available in the industry (e.g. Air Line Pilots Association Air Safety Team, 2010; The European Organisation for the Safety of Air Navigation, 2011c; The International Federation of Air Line Pilots' Associations, 2009).

The models developed by academia are designed to be used for risk assessments. Some of these studies also provide recommendations for the mitigation of risk factors associated with excursions (The European Organisation for the Safety of Air Navigation, 2010d). Often, however, the focus is on the development of the statistical models and recommendations for their application for risk assessments and not on the proposal of mitigation measures (Es, 2005; Es*, et al.*, 2009; Hall*, et al.*, 2008).

Recovery risk controls on the other hand, aim to mitigate the effect of an excursion and act in situations where an aircraft actually experiences an excursion.

Recovery risk controls include technological solutions such as engineered material arresting systems (EMAS), which use a light-weight, crushable concrete material, placed beyond the end of the runway, to stop or greatly slow down an aircraft that overruns the runway, as shown in Figure 49 (Federal Aviation Administration, 2008b).



Source: Port Authority of New York and New Jersey (2003)

Figure 49: Engineered materials arresting system

In summary, the following conclusions are drawn from the research to date on excursions:

- Research on excursions is mainly initiated by accident investigation bodies, safety consortia and academia, but not by the stakeholders directly involved in excursions;

- The research is limited in scope, i.e. runway-related excursions are not considered in a holistic manner (i.e. by inclusion of all excursion types) and both incidents and taxiway-related occurrences are neglected;
- The causal factors are aggregated at a global level;
- The causal factors are always derived from safety data, alternative methodologies (e.g. interviews with SMEs) are missing;
- Methodologies on how the causal factors have been extracted from safety data are not specified in the majority of cases;
- Most studies are of qualitative nature and do not go beyond descriptive statistical analysis;
- There is a lack of robust statistical modelling of causal factors (e.g. the functional relationship between causal factors and the severity of excursions) to identify the most critical causes in order to guide safety mitigation efforts more effectively;
- Data of potentially differing qualities is aggregated and data quality issues are not addressed.

The limitations shown above are similar to those identified for incursions and will be addressed in this thesis through a holistic (integrated) approach to safety. The detailed research outline based on these limitations is presented in section 5.3.

5.2.4 FOD

FOD is a multi-million dollar problem in the aviation industry. For instance, a study by McCreary (2008) estimated that the top 300 airports (in terms of movements) in the U.S. see up to 70,000 FOD incidents per year, which incur direct costs of US$ 1.1 billion to airlines (e.g. for engine maintenance, tire replacements, aircraft body damage). If indirect cost such as delays, plane changes, or fuel inefficiencies are added then the cost of FOD increases to US$ 12 billion per year in the airline industry.

Although FOD is a costly problem, it is not addressed as extensively in the literature as the other safety issues discussed in this chapter. Eight documents have been reviewed to identify the possible causes of FO and FOD mitigation measures. Publishing bodies included aircraft manufactures (Bachtel, 2010), regulators (Federal Aviation Administration, 1996, 2009a, 2010b), airport operators (MBJ Airports, Year not specified), consultants (Prather, 2011), aerospace industry consortia (National Aerospace FOD

Prevention Inc, Year not specified), safety consortia (The European Organisation for the Safety of Air Navigation SKYbrary, 2013b, c), and technology companies (Kraus and Watson, 2001; The FOD Control Corporation, 2010). In addition, airline FOD prevention programmes have been reviewed (e.g. Delta Air Lines, 2011; United Airlines, 2010). Most of these documents are not research studies but rather compilations of knowledge in the area of FO(D). In fact, there is no academic literature on the analysis and prevention of FO(D). Most studies originate in the U.S. and although different terminologies are used, they all refer to debris that can lead to damage. Appendix II Table 3 summarises the reviewed documents in terms of the data sets, data quality issues, analytical methodologies, results, strengths and weaknesses.

5.2.4.1 Causal Factors

The majority of documents do not state the causes of FOD. Typically the source of the FO is mentioned and examples are given, and therefore, the causal factors can only be implied. Table 19 summarises the main sources of FO in eight categories.

Table 19: High-level sources of FOD

Causal factors	Bachtel (2010)	Federal Aviation Administration (1996, 2009a, 2010b)	MBJ Airports (Year not specified)	National Aerospace FOD Prevention Inc (Year not specified)	Prather (2011)	The European Organisation for the Safety of Air Navigation SKYbrary (2013b, c)	The FOD Control Corporation (2010)
Airport infrastructure	✓		✓	✓	✓	✓	✓
Aircraft		✓	✓		✓	✓	✓
Vehicles		✓	✓		✓	✓	✓
Maintenance / construction	✓	✓	✓	✓	✓	✓	✓
Ground handling	✓		✓		✓	✓	✓
Personal belongings	✓	✓	✓		✓	✓	✓
Environment		✓	✓	✓	✓	✓	✓
Weather		✓	✓	✓	✓	✓	

There are various sources of FO. For instance, FO can develop from the airport surface infrastructure, e.g. through the deterioration of pavements (e.g. pieces of concrete can break loose from holes in the pavement), or runway and taxiway signs and lights. Similarly, aircraft and vehicles can generate FO. Nuts and bolts, carbon parts, fuel caps, or

other small parts that fall off from aircraft, vehicles, fuelling trucks, construction and maintenance equipment, etc. are commonly found on the manoeuvring area. The maintenance of surface infrastructure, aircraft and vehicles can also cause FO when, for example, tools, bolts or wires are forgotten in an aircraft or vehicle. A further source of FO is construction work on the airport surface.

The operations involved in aircraft handling on the apron can also cause FO, which can eventually end up on a taxiway or runway. Common FO sources include refuelling, catering supplies, cabin cleaning and garbage, and baggage (e.g. baggage tags). In addition, cargo handling can produce broken materials, paper products and plastics. Personal belongings from operational personnel are also a common source of FO. These include pens, coins, identification badges, hats, soda cans, paperwork, and any other object that airport or airline personnel carry and inadvertently leave in an inappropriate location. Likewise, personal belongings of passengers can be found on the airfield. Finally, FO can be generated by the environment (e.g. stones, sand, pieces of wood, ash) and the weather (ice, hail).

Only Kraus and Watson (2001) explore the causes of FO rather than just the sources. The authors refer to the National Aerospace Standards (NAS 412) to suggest that most FO is attributable to poor housekeeping, deterioration of facilities, improper maintenance and inadequate operational practices. Kraus and Watson also add to these four factors management and organisational interaction and support, FOD awareness, FOD training, and FOD audits and inspection. Other classifications of FO into FO type (Federal Aviation Administration, 2010b), or the size of FO objects (McCreary, 2010) can also be found in the literature.

5.2.4.2 Analytical Methodologies and Data Quality Issues

Out of the eight documents reviewed, seven provide a compilation of knowledge and are not based on an analysis of data. Often, it remains unknown where this knowledge has been compiled from (Bachtel, 2010; MBJ Airports, Year not specified; The European Organisation for the Safety of Air Navigation SKYbrary, 2013b; The FOD Control Corporation, 2010). Only three documents reference existing literature and FOD standards (Kraus and Watson, 2001; National Aerospace FOD Prevention Inc, Year not specified) or research studies (Federal Aviation Administration, 2009a). These documents are purely

descriptive and contain the sources of FO, elements of FOD control programmes and / or available technologies that support FO detection. These mitigation strategies will be discussed in more detail in the next section.

Only Prather (2011) reviews the existing literature and contributes to it with a stakeholder survey. The study falls into category 2 of the analytical methodologies introduced in Figure 47. The author surveys airports as well as technology companies to enquire about current FOD management practices and available technologies for FO detection and prevention. The results are presented in response frequencies.

5.2.4.3 Safety Risk Mitigation Strategies

A successful FOD control programme consists of several components, and the literature describes each of these to varying degrees. Although the number of elements differs in the literature, they can be summarised into three cornerstones:

- Prevention
- Detection / removal (inspection and detection, removal, evaluation, and documentation)
- Support (management support and FOD awareness; training and education).

FOD prevention is a proactive approach that aims at avoiding FO and measures include FOD containers that can be placed at all gates for the collection of debris, magnetic bars that can be suspended beneath vehicles to pick up metallic material, and rumble strips that dislodge FO from vehicle undercarriages when driving over them (Bachtel, 2010).

FO detection and removal is a reactive approach. This includes FO inspections, such as airfield inspections that are carried out at regular intervals during the day, and FO detection equipment, i.e. continuous monitoring systems to assist FO inspections.

FOD detection technologies include radar-based, electro-optical, and hybrid systems. Radar-based systems use radio transmission data as the primary means to detect FO on the airport surface. These systems can be stationary or mobile. Stationary radar detection systems use sensors located at the runway edge and are able to detect metallic cylindrical objects (3 x 3.8 cm) within one kilometre. Mobile radar detection systems are mounted on top of vehicles and scan the surface in front of the vehicle when moving.

Electro-optical systems use technology and image processing data to detect FO on the manoeuvring area. These systems are able to detect objects that measure at least 2 cm at a range of up to about 300 m using only ambient lighting.

Hybrid systems use a combination of radar and electro-optical data as the primary means to detect FO on runways and taxiways. Both radar and electro-optical sensors are collocated with the runway edge lights, and the system is able to detect objects that measure at least 2 cm (Federal Aviation Administration, 2009a).

After FO has been detected a critical aspect of a FOD control programme is the actual removal of the FO as promptly as possible without undue interference with airport operations. It is the airport operator's duty to ensure that this part of the process is conducted in the most professional and conscientious way possible. After the FO has been removed it needs to be properly documented and analysed. Keeping track of FO(D) events (e.g. type of FO and the location where it was found) is vital in order to monitor trends and to perform risk analyses. In this way, problem areas can be identified and countermeasures developed (Prather, 2011).

Finally, a FOD control programme needs a support system that encourages both preventive and reactive activities. Management support is key for the development of any FOD control programme and should encourage a FO(D) awareness and prevention culture throughout the organisation. In addition, all operational personnel should receive FO(D) prevention and elimination training in order to increase their awareness of the causes and effects of FO(D) (Kraus and Watson, 2001).

In summary, the following conclusions can be drawn from the analysis of the FOD-related literature:

- FOD occurrences are the subject of the least literature of all the airport surface accidents / incidents;
- The few documents available are published by the industry, with academic literature on FOD occurrences entirely lacking;
- Publications are mostly of a qualitative nature;
- The causal factors of FOD are largely unexplored with studies only stating FOD sources and examples of FOD, and therefore, robust causal factor assessment studies are lacking.

Overall, FOD is the occurrence type that is addressed least, although the economic costs of FOD are high. There are three possible explanations for the lack of research on FOD. Either it is not recognised to be as problematic as other occurrence types (e.g. excursions / incursions), or it is dealt with at an organisational level and not published; or both.

5.2.5 Wildlife Strikes

In contrast to FOD occurrences, the literature on wildlife strikes is extensive, and over 50 studies and documents have been identified that discuss bird and mammal attractants, wildlife control programmes and / or the risk to aviation caused by animals. To provide an insight into wildlife mitigation and research for airports, 20 documents were chosen and reviewed so as to reflect the initiatives of all the relevant aviation stakeholders. In particular, major industry initiatives, and papers that reflect the various strands of academic research were selected.

Studies published by all stakeholders that have an interest in wildlife strikes include aircraft manufacturers (Airbus, 2004a), airports (Dao-De*, et al.*, 2010), airport associations (Australian Airports Association, 2005), regulators (International Civil Aviation Organization, 1991; Maragakis, 2009; Transport Canada, 2002, 2010a; UK Civil Aviation Authority, 2008a), accident investigation boards (Australian Transport Safety Bureau, 2008a), industry consortia (Cleary, 2007; International Birdstrike Committee, 2006; The European Organisation for the Safety of Air Navigation SKYbrary, 2013a), consultants (Nikolaidis and Koloka, 2005), research institutes (Allan, 2006; Dennis and Lyle, 2009; Manktelow, 2000), and academia (Fennessy*, et al.*, 2005; Hesse*, et al.*, 2010; Soldatini*, et al.*, 2010; Steele, 2001). In addition, several dedicated wildlife strike committees (e.g. Bird Strike Committee USA, 2013; Deutscher Ausschuss zur Verhuetung von Vogelschlaegen im Luftverkehr e.V., 2013; International Bird Strike Committee, 2013) share their knowledge with the aim of reducing occurrences involving wildlife.

The reviewed documents confirm the disagreement in regard to definitions (see section 4.5.5). Studies refer either to bird strikes only, to wildlife in general, or to ‘bird strikes’ that misleadingly include mammals as well as birds. The reviewed studies were published worldwide, including North America, Europe, Oceania, and Asia and are shown in overview in Appendix II Table 4.

5.2.5.1 Causal Factors

As with FO, for wildlife strikes it is often not possible to identify their direct cause, and therefore, most studies refer to wildlife attractants (UK Civil Aviation Authority, 2008a), risk factors (Soldatini*, et al.*, 2010), variables affecting the incidence of strikes (Steele, 2001), or circumstantial factors (Australian Transport Safety Bureau, 2008a).; these are factors that contribute to the presence of wildlife at airports, i.e. increase their likelihood, or define the circumstances under which wildlife strikes occur. These factors are referred to as *contributing factors* throughout this thesis. Overall, the factors discussed above can be grouped into eight categories, which include bird and mammal attractants inside the airport as well as outside of it. Table 20 summarises the factors identified in 15 of the documents that contained contributing factors.

The most common wildlife attractants mentioned in the literature are shelter and food and water sources. Food sources include mice, insects, earthworms, snails, slugs, spiders, trees and bushes with fruits and berries, and waste from in-flight or terminal catering areas. Open standing water and other water sources include open drainage ditches, ponds and wet and waterlogged grass. Shelter can be found in buildings and building structures with access holes, hangars, radar towers, as well as in trees and bushes, grass and wooded zones. Sources of food, water and shelter outside the airport can likewise attract wildlife. The nature of the land use surrounding the airport can also serve to attract wildlife, such as coastal areas, moorlands, landfill sites, sewage treatment and disposal facilities, parks and picnic areas, reservoirs, lakes and ponds, and agricultural attractants (e.g. crops, livestock). Next to food, water and shelter, seasonal and temporal factors (e.g. month, time of the day / visibility, and migration paths of birds), weather (e.g. rainfall and wind) and temperature all influence the presence of wildlife at airports. Finally, flight operations (e.g. phase of flight, aircraft speed) and airport operational factors (e.g. tranquillity, presence of humans, machines and equipment) have been identified in the literature as circumstantial factors and wildlife attractants, respectively.

These eight categories are consistently mentioned in the literature and appear to be relevant throughout the different regions of the world. In fact, they were for the most part already identified in the early study of Laty (1982) and are still valid today.

Table 20: High-level causal factors for wildlife strikes

Causal factors	Australian Airports Association (2005)	Australian Transport Safety Bureau (2008a)	Dennis and Lyle (2009)	Fennessy, *et al.* (2005)	Hesse, *et al.* (2010)	International Civil Aviation Organization (1991)	Laty (1982)	Manktelow (2000)	Maragakis (2009)	Nikolaidis and Koloka (2005)	UK Civil Aviation Authority (2008a)	Soldatini, *et al.* (2010)	Steele (2001)	The European Organisation for the Safety of Air Navigation SKYbrary (2013a)	Transport Canada (2002, 2010a)
Food sources at the airport	✓				✓	✓	✓			✓	✓	✓	✓	✓	✓
Water sources at the airport	✓				✓	✓	✓			✓	✓	✓	✓	✓	✓
Shelter at the airport	✓				✓	✓	✓			✓	✓	✓	✓	✓	✓
Airport surrounding land use	✓				✓	✓	✓		✓	✓	✓			✓	✓
Seasonal and temporal factors	✓	✓		✓			✓		✓			✓	✓	✓	✓
Weather	✓						✓	✓					✓		
Flight operations factors		✓	✓						✓			✓	✓		✓
Airport operations	✓						✓					✓			

5.2.5.2 Analytical Methodologies and Data Quality Issues

Five of the reviewed documents are not based on data and are purely descriptive. These, therefore, fall into category 1 of the analytical methodologies that were introduced in Figure 47. They describe bird / mammal attractants (Laty, 1982), give recommendations for wildlife control (Australian Airports Association, 2005; International Birdstrike Committee, 2006), or in some cases even both (The European Organisation for the Safety of Air Navigation SKYbrary, 2013a; UK Civil Aviation Authority, 2008a).

The majority of the analysed studies fall into category 2 of the analytical methodologies, i.e. studies that are based upon data but which do not go beyond descriptive statistical analysis. These studies use historical wildlife strike data or observations and bird counts at airports to analyse wildlife strike trends (Fennessy*, et al.*, 2005; Maragakis, 2009), identify circumstantial and risk factors (Australian Transport Safety Bureau, 2008a), or determine the damage wildlife can cause to aircraft (Airbus, 2004a; Dennis and Lyle, 2009). Some studies also provide recommendations for wildlife control and management based upon their results (Hesse*, et al.*, 2010; International Civil Aviation Organization, 1991; Nikolaidis and Koloka, 2005; Transport Canada, 2002, 2010a).

Rarely, studies go beyond descriptive statistics and use statistical analyses to identify the circumstances under which wildlife strikes occur. For instance, Manktelow (2000) and Steele (2001) use statistical associations to analyse the influence of weather (e.g. rainfall, temperature) on the occurrences of bird strikes.

Statistical analysis is also used to model the risk associated with wildlife strikes. Allan (2006) determines the bird strike risk per bird species at UK airports by estimating the strike probability and severity (i.e. safety risk) based on historical strike data. However, Fennessy*, et al.* (2005), showed that the profile of strikes does not closely reflect the profile of species present at the airport. Therefore, risk assessments should also take into account historical data regarding the risk imposed by birds that are present at an airport even if they have not yet been involved in a strike. On the other hand, Dao-De*, et al.* (2010) model the threat of birds to aircraft using observations and bird counts. The authors defined 11 risk factors (e.g. bird encounter frequency, population size, residence time) and recorded and scored these factors during observations. A risk value was then calculated for

each species as the product of the scores of the bird strike risk factors. Subsequently, the birds were divided into prevention groups by different risk levels using hierarchical cluster analysis. By this means, the authors considered the risk to aviation that is imposed by the presence of birds at an airport and their behaviour. A similar approach was adopted by Soldatini*, et al.* (2010), who develop a bird strike risk index (BRI) that describes the risk for an airport on the basis of the actual presence of birds. Future research should explore the benefits of combining these different approaches.

Another strand of research is concerned with wildlife damage modelling on aeronautical structures in order to improve aeronautical composite structures and to verify certification requirements (Ivancevic and Smojver, 2011; Smojver and Ivancevic, 2010, 2012). Since the focus of this thesis is on the determination of causal factors and their mitigation these studies were not reviewed in detail.

Among the 20 documents and studies reviewed only Transport Canada (2010a) acknowledges data quality, evaluating their underlying dataset as underreported. The absence of discussions on the quality of wildlife strike reporting raises questions about the reporting level and quality of data about reported strikes.

5.2.5.3 Safety Risk Mitigation Strategies

In order to mitigate wildlife strikes each airport should develop and implement a wildlife management programme. Wildlife management and control programmes are based on four pillars. The primary objective is to *deter* wildlife from the airport and its vicinity. This includes, in the first instance, the identification and removal of wildlife attractants through habitant management and fencing. Habitant management refers to activities aimed at removing wildlife attractants, reducing them in quantity, or denying access to them, such as vegetation modification, removal of trees and bushes, installation of drainage, and the use of netting to exclude wildlife from water bodies and from buildings. If wildlife enters the airport effective wildlife control requires that birds / mammals are *dispersed* as soon as possible through e.g. visual methods (e.g. lasers, “eyes”, fake predators) or acoustic methods (e.g. radio controlled sound generators, cannons, bangers, pyrotechnic pistols). After exclusion or repellent methods have been exhausted wildlife needs to be *removed*. Lethal methods include poisoning, trapping, falconry, and sharp shooting (Dragonas, 2012;

Hesse*, et al.*, 2010; International Birdstrike Committee, 2006). It is important that wildlife control does not stop within the boundaries of the airport, but is extended to its vicinity, i.e. 13 km from the aerodrome reference point, so as to ensure the safe approach and ascent of aircraft (UK Civil Aviation Authority, 2008a). Finally, effective wildlife management requires the *reporting* of wildlife and wildlife strikes and their analysis.

In summary, the following conclusions are drawn from the research to date on wildlife strike analysis and prevention:

- The threat of wildlife to aviation is addressed by all relevant stakeholders from the industry as well as by academic research;
- The majority of published studies focus on bird strikes rather than wildlife in general;
- Wildlife attractants and circumstantial factors have not changed over time and are acknowledged worldwide;
- Two types of data collection methods have been identified for wildlife: historical strike data, and observations and bird counts, but these have only been used in isolation;
- The majority of studies are purely descriptive or are based on qualitative data analyses (e.g. frequency analysis);
- Data quality is typically not addressed, and therefore questions concerning the appropriateness of wildlife data and the level of reporting have been raised.

5.2.6 Initial Taxonomy of Causal Factors Underlying Airport Surface Safety Occurrences

The factors identified in the literature are summarised in an initial taxonomy that describes the causes and contributors underlying all airport surface safety occurrence types. A total of 350 factors were identified based on 65 relevant reports and used to construct this initial taxonomy. The factors can be classified into human, technical, airport design, environmental and regulatory factors, and are shown in Figure 50.

The following section analyses whether taxonomies exist to adequately describe the context of airport surface safety by capturing the entirety of the factors introduced above.

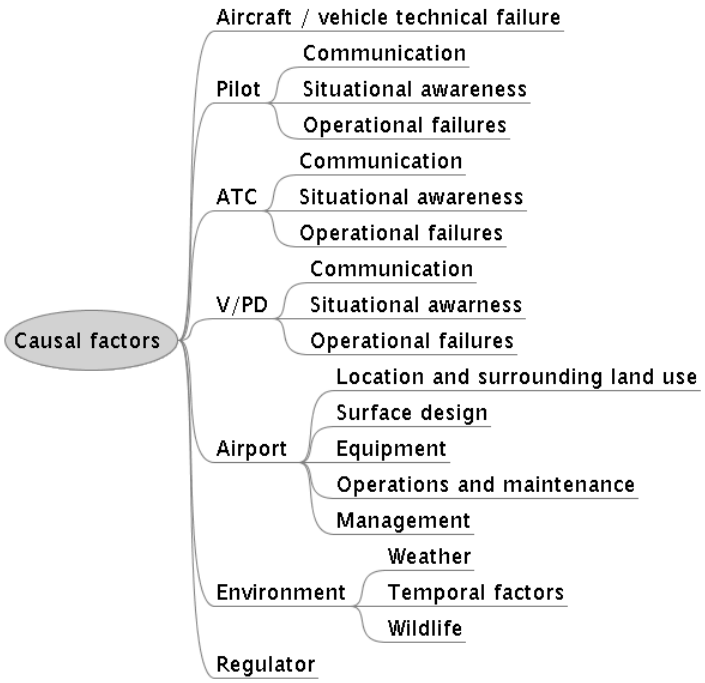


Figure 50: Causal factors identified through literature search

5.2.7 Taxonomies

A taxonomy is "a scheme of classification" (Oxford Dictionaries, 2013) and, in particular, within the context of this research, a classification of causal factors of airport surface accidents and incidents. Taxonomies provide terminology for the subject matter and a framework for research, and are often used to systematise safety data according to pre-defined codes (Australian Transport Safety Bureau, 2008b, 2009; Es, 2005; The European Organisation for the Safety of Air Navigation, 2010d). Each causal factor within the taxonomy is thereby assigned a number (code). The descriptive narrative of occurrence reports is analysed and once a cause is identified from the data, the particular code is assigned to the occurrence. Coding the data allows for subsequent statistical analysis.

The literature is inconsistent concerning the terminology. Whereas some studies refer to the term taxonomy (International Civil Aviation Organization, 2006a; UK Civil Aviation Authority, 2008b), others propose classifications of causal factors (Flight Safety Foundation, 2009), or data coding forms (International Civil Aviation Organization, 2007; Khatwa and Helmreich, 1999). Essentially, however, these terms each refer to the same thing, i.e. a classification scheme. Table 21 summarises the major existing taxonomies and classification schemes, their advantages and limitations, as well as their scope and potential for application to surface safety occurrences.

Table 21: Taxonomies

Reference	Potential application	Advantages	Disadvantages
ADREP Common Taxonomy (International Civil Aviation Organization, 2006a)	• Generic aviation	• Global ICAO standard • Contains event types, descriptive and explanatory factors in a great level of detail	• Designed for generic aviation safety occurrences • It captures many factors that do not apply for the investigation of surface safety occurrences and would therefore overcomplicate any analysis • Too comprehensive and detailed, e.g. causal factors that are hard to capture during an incident investigation are included (e.g. personality factors)
CAST/ICAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2008a)	• Generic aviation	• Large-scale international effort to develop common taxonomies for aviation accident and incident reporting systems • Global standard as it is incorporated in other international taxonomies (e.g. ICAO ADREP, FAA Aviation Safety Information Analysis and Sharing (ASIAS))	• Limited to standard aviation definitions, causal factors are not included
Aviation Safety Reporting System (ASRS) (National Aeronautics and Space Administration, 2010)	• Generic aviation	• Event types and their contributing factors	• Contributing factors to events lack an appropriate level of detail and are given in too broad categories (e.g. 'equipment', 'human factors')
Accident Analysis Group (AAG) Taxonomy (UK Civil Aviation Authority, 2008b)	• Excursions and collisions	• Reasonable classification • Taxonomy differentiates between causal and circumstantial factors	• Developed based on a study of worldwide fatal accidents, no incidents were considered • Wildlife strikes and FOD are not considered as possible consequences of an accident • Not encompassing enough as factors such as e.g. 'communication' are missing
Approach-and-Landing Accident Coding	• Excursions and runway collisions	• Reasonable classification	• It includes factors that do not apply to

Form (Khatwa and Helmreich, 1999)		• Taxonomy differentiated between causal and circumstantial factors	the scope of this research as it considers approach-and-landing-occurrences • Developed based on a study of accidents, no incidents were considered
Approach-and-Landing Accident Reduction (ALAR) Tool Kit (Flight Safety Foundation, 2000)	• Excursions	• Reasonable classification	• Only applicable for excursions • Reasonable categories are proposed, but the tool kit fails to specify them in detail • The category of 'system factors' seems to be too broad
Common Risk Factors in Runway Excursion Events (Flight Safety Foundation, 2009)	• Excursions	• Latest industry effort for excursions • Reasonable classification with detailed causal factors	• Developed based on a study of accidents, no incidents were considered • Only applicable for excursions • The category of 'system factors' seems to be too broad
Risk Analysis Tool (RAT) (The European Organisation for the Safety of Air Navigation, 2011b)	• Collisions	• Latest industry effort for collisions • Reasonable classification • Fully compliant with ADREP	• Only applicable for collisions and incursions • Takes on an ATM perspective and therefore factors for e.g. airport operations (e.g. vehicle driver / pedestrian) are missing
Runway Incursion Causal Factors Identification Form (International Civil Aviation Organization, 2007)	• Runway incursions	• Comprehensive coding form for the causal factors that underlie runway incursions • Reasonable classification	• Only applicable for runway incursions • Focuses mainly on human factors, system factors such as e.g. weather are missing

Generic aviation taxonomies, such as the ICAO ADREP system, whilst very detailed, are inappropriate for this research. ADREP comprises causal factors for all aviation safety occurrences and hence, contains numerous aspects that do not apply to the scope of this research and thereby would complicate an analysis of surface safety data.

Classification schemes for single occurrence types suffer from the same limitations as highlighted in the previous sections. Firstly, their scope is limited towards the consideration of one occurrence type. In addition, the majority of approaches suffer from focusing only on runway-related occurrences. Taxonomies for the causal factors of wildlife strikes and FOD are missing entirely. Secondly, these classification schemes have been developed primarily using just one research method. For instance, the FSF taxonomy (Flight Safety Foundation, 2009) is based on an analysis of accident data, and the ICAO coding form (International Civil Aviation Organization, 2007) on a consensus of subject matter expertise. Furthermore, these classification schemes fail to capture the different perspectives of the stakeholders involved in surface safety occurrences.

In addition to a theoretical review, the most promising single occurrence taxonomies for incursions and excursions that seemed most promising were tested to assess their fit to a real data set and their applicability for data analysis. The taxonomies chosen were the ICAO Runway Incursion Causal Factors Identification Form (International Civil Aviation Organization, 2007) and the FSF Common Risk Factors in Runway Excursion Events (Flight Safety Foundation, 2009). The ICAO runway incursion classification scheme was chosen, since the literature review identified it to be the most comprehensive scheme for incursions, with the best classification structure. It contains communication, pilot, ATC and V/PD factor as well as factors related to the airport physical infrastructure and regulations, which have been identified as the main drivers to incursions in section 5.2.2.1. If the coding form is well developed, it should be applicable to any data set that is collected from a country that follows ICAO regulations and applies its definitions.

To test it, a data set from a representative European ANSP in compliance with ICAO regulations and definitions was collected. For sensitivity reasons the identity of the organisation cannot be not revealed. Structured communications with a senior SMEs from EUROCONTROL confirmed that the organisation is known in the industry for a good safety culture and thus the data has been evaluated as reliable (Structured communication with EUROCONTROL Head of Safaty Unit and Retired EUROCONTROL Head of Safety Regulations, 2010).

The data was coded using the classification scheme and the coding form appeared inadequate. One example will highlight this. The factor 'pilot did not contact the ATC in the first instance' was analysed from the data and refers to a situation where an aircraft did not initiate any contact to ATC and started moving on the manoeuvring area. In the ICAO coding form, causal factors refer to those that can occur after a contact between an aircraft and ATC was initiated, such as communication problems, misunderstanding or the misuse of clearances. However, the ICAO coding form does not account for a case when no initial contact was established between the aircraft and ATC. This example indicates that the ICAO coding form is incomplete and does not capture all causal factors that underlie airport surface accidents and incidents. In addition, it refers to runway incursions only and fails to capture taxiway occurrences. An explanation for the lack of fit between the ICAO coding form and the incident database could be that ICAO developed the causal factors based upon a consensus of subject matter experts, though without an analysis of real data. This highlights that a single analysis method on its own is inadequate to develop a taxonomy.

Similar conclusions were drawn when testing the Flight Safety Foundation (2009) classification scheme of causal factors underlying excursion accidents against a real data set. The classification was used to code a dataset of excursions captured by the FAA Accident and Incident Data System (AIDS). The AIDS database is publically available and contains incident data for all occurrence categories of civil aviation and will be introduced in more in detail in Chapter 6 section 6.6.2. For excursions, the FSF taxonomy was chosen for a trial data analysis, as it is the latest industry effort developed on a global basis and seems to be the most encompassing classification scheme among those involving excursion, i.e. the classification scheme captured the causal factors underlying excursions identified in section 5.2.3.1 best. The FSF defines an excursion as either a veer-off or an overshoot. The AIDS database captures veer-offs, overshoots and undershoots. As undershoots were not considered in the FSF analysis those occurrences were excluded from the trial. Again, not all critical factors found in the data could be assigned to a factor from the taxonomy.

In summary, the commonly practiced piecemeal approach fails to capture the full context of causal factors. In addition, the lack of an appropriate taxonomy for the causal factors of surface safety occurrences inhibits high quality research in safety.

5.2.8 Summary of Findings on Surface Safety Modelling

The two main findings from the review of the literature on surface safety modelling are the following. Firstly, studies analyse single accident / incident types and no research exists that examines surface safety in an integrated manner. A holistic approach would enable the interactions between the occurrence types to be considered. Secondly, studies typically reflect the perspective of individual stakeholders (e.g. analysis of regulatory data, interviews with pilots only). Approaches that combine the complementary views of the relevant stakeholders do not exist.

In addition, the following limitations were identified in the literature:

- Aviation stakeholder address the occurrence types that lie within their sphere of interest and responsibility (e.g. ATC has no immediate interest in FOD, it is the airport operator's responsibility and in the airline's interest to keep the surface FOD free);
- There is a strong focus on runway-related occurrences only;
- Analyses are based upon insufficient and misleading definitions;
- Causal factor analyses capture the factors mainly from the perspective of one party involved in surface safety occurrences (e.g. regulator, pilot, ANSP, airport operator). These studies fail to provide an overview of the causal factors from the perspective of all aviation stakeholders involved in the subject matter;
- Studies mainly apply one research method to determine the causal factors (e.g. data analysis, interviews, case studies), but lack combined approaches that would enable a more complete picture of the subject matter;
- Analyses of causal factors that are based on safety data lack often a clear and scientifically rigorous methodology concerning how the causal factors have been extracted;
- The majority of causal factor analyses are of a qualitative nature and do not go beyond descriptive statistical analysis;
- The identification of causal factors is not accompanied by information such as geographical distributions, factor combinations and interactions;
- Data quality is rarely addressed in the context of airport surface safety;
- No research has questioned the accuracy of the data;
- The industry lacks integrated databases;

- Databases with potentially differing qualities are aggregated;
- Underreporting for some data sources (e.g. wildlife) has been indicated;
- The literature lacks robust statistical modelling of causal factors (e.g. the functional relationship between causal factors and severity of occurrences) to identify the most critical causes in order to guide risk mitigation efforts more effectively;
- There are no taxonomies of causal factors covering the various elements of airport surface safety. Generic aviation taxonomies are detailed and consider all types of aviation safety occurrences and thus contain many aspects that do not apply to surface safety and would overcomplicate the analysis. Classification schemes for single occurrence types exist only for incursions and excursions. On the basis of their methodology, these schemes were evaluated as insufficiently detailed to cover the causal factor from all perspectives.

To conclude, there is a need for a holistic (integrated) approach to airport surface safety. To date the safety of the airport surface system has been considered both adhoc and piecemeal (i.e. consideration of single occurrence types from the viewpoint of individual stakeholders). This is a matter of concern since, as Chapter 3 has shown, the system relies on the input of various stakeholders and cannot function without their cooperation. Overall, the piecemeal approach that characterises airport surface safety violates the principles of SMS, in which it is recognised that the whole system (i.e. all components and their interactions) should be assessed for hazards. That runway safety is a multidisciplinary problem and requires the cooperation of stakeholders has also been acknowledged by the ICAO (International Civil Aviation Organization, 2011c), however, the literature review conducted here has shown that, so far, little effort has been put into the realization of this aspiration.

Based on the problems associated with the scope of analysis, definitions, data and taxonomies it can be concluded that essential fundamentals of SMS and operational safety risk management are missing. This thesis, therefore, addresses the four components of SMS and recommends major enhancements as outlined below.

5.3 A Holistic Approach Towards Surface Safety

The industry currently lacks tools and guidelines for a robust airport SMS. To begin to address these omissions, the following research requirements have been derived from the findings of Chapters 2 to 5:

- Integrated safety assessment of the airport surface system through:
  - Consideration of all airport surface safety occurrence types (on runways and taxiways), and
  - Consideration of all components and relevant stakeholders of the system and their interactions;
- Qualitative and quantitative assessment of the relationship between causal factors and airport surface safety occurrences;
- Combination of different research methods to explore the causal factors in depth;
- Utilisation of the new definitions proposed in the previous chapter to ensure the consideration of all aspects of surface safety;
- Utilisation of data from organisations that actively promote safety and reporting (SMS requires a data-driven approach and the central role of safety data also emerged during the literature review); and
- Assessment of data quality to ensure a high quality of safety data.

To overcome the limitations of previous research this thesis proposes a framework for an integrated assessment of airport surface operations that supports the four cornerstones of SMS. In particular, a holistic model of airport surface safety is developed and Figure 51 outlines the research and its contributions to SMS.

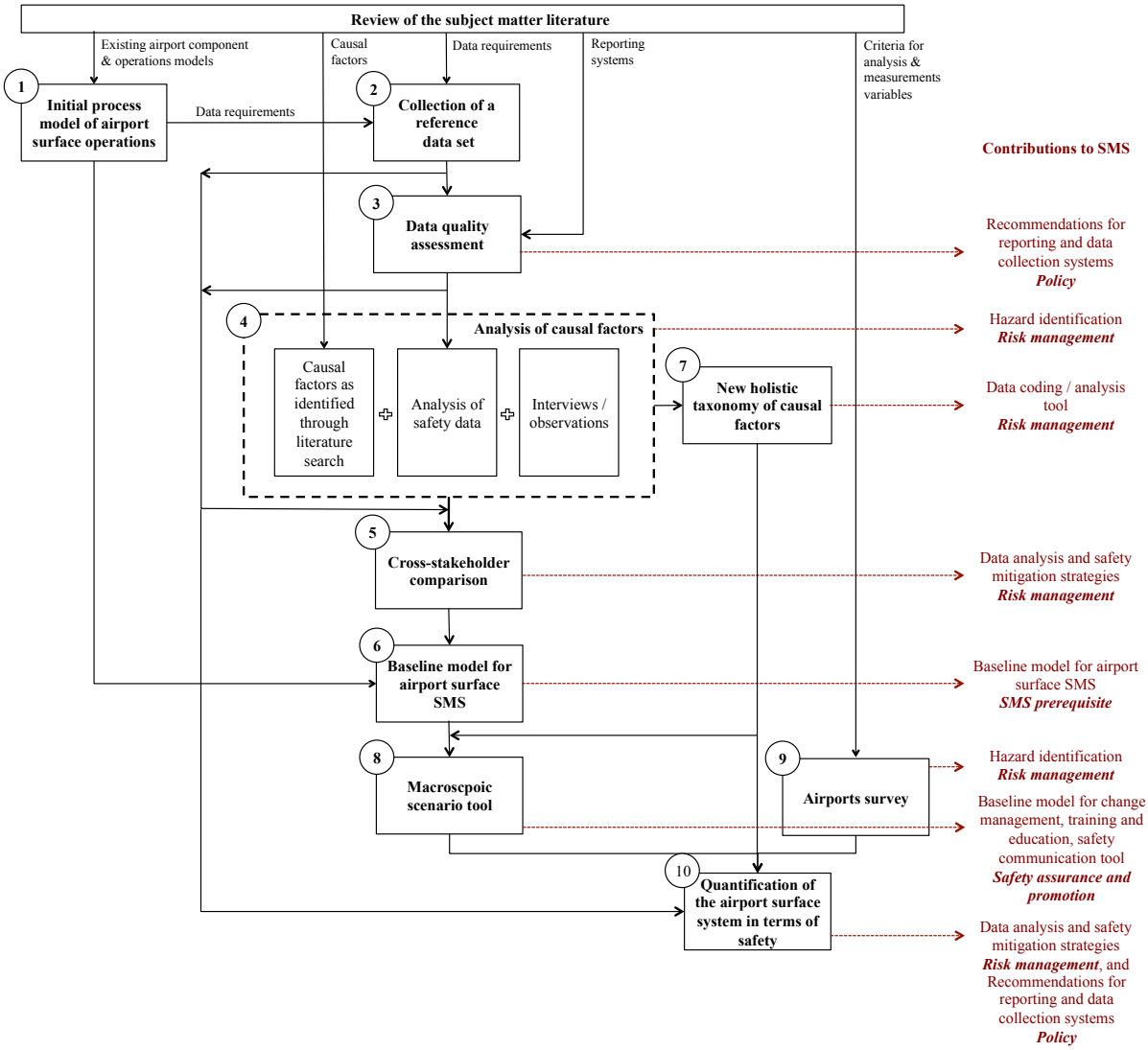


Figure 51: Research outline

Unlike current airport surface safety management practices, the proposed model assesses the safety of the operations of all relevant actors. A system architecture, which describes the tasks and interactions of the stakeholders and the physical airport surface infrastructure, has already been developed in Chapter 3. This forms an initial baseline model that will guide the further development of the proposed SMS.

To manage the safety of surface operations, however, the causes of accidents and incidents must be identified and their impacts understood. To this end, Chapter 6 collects a reference data set that combines twelve databases from airlines, airport operators, ANSPs, ground handling companies and regulators. Prior to its analysis, the data is assessed for its quality, and in particular, for its internal validity (i.e. precision), external validity (i.e. accuracy) and in terms of reporting levels. A novel external data validation framework is

developed and each database is rated with a data quality index (DQI). In addition, recommendations for reporting systems and safety policies are given. The causal factors are subsequently extracted from the data by analysing the descriptive narrative of each occurrence report. Afterwards, the databases are compared across stakeholders and the contributions of the individual actors are highlighted (Chapters 7 and 8). The analysis is complemented by interviews, observations and statistical analysis, and the results are summarised in a new taxonomy (Chapter 9). This taxonomy is applicable to all relevant stakeholders and is recommended for their operational safety risk management. In addition, the findings from the analysis of causal factors are used to refine the initial baseline model and to update the airport surface system architecture.

After the airport surface operations have been modelled and the drivers to safety identified, the results are combined, resulting in a macroscopic scenario tool which supports the management of change (i.e. safety assurance), training and education, and safety communication (i.e. safety promotion) functions of SMS (Chapter 9). Finally, a structured framework to assess the functional relationship between airport surface accidents / incidents and their underlying causal factors is proposed and the system is quantified in terms of safety (Chapter 11). The relevant data is collected through an airports survey (Chapter 10). Overall, the holistic approach to surface safety allows resources to be directed more effectively towards the development of robust solutions for airport surface safety analysis and mitigation.

5.4 Summary

This chapter provided an integrated state-of-the-art review regarding the current status of airport surface safety analysis and risk mitigation. It identified the limitations in regards to causal factor and airport surface safety research in terms of analysis scope, data, methodologies, and taxonomies, and highlighted the lack of, and need for, an integrated approach. In addition, an initial taxonomy of the causal factors that underlie airport surface safety occurrences has been developed. Based upon the findings from Chapters 2 to 5 research requirements have finally been derived and a framework for an integrated

assessment of airport surface operations proposed and outlined. In so doing, this chapter has fulfilled the third research objective.

The next chapter discusses the specification and execution of a data capture scheme, for the analysis of the safety of the airport surface system.

6 Data Collection and Validation

Chapter 5 identified the limitations of previous research, including the limited scope of airport surface safety analysis, and the use of insufficient data and methodologies. This chapter addresses these limitations by developing a scheme for the collection of a reference dataset, and a framework for the assessment of the quality (i.e. validation) of data. The validated data are analysed to determine the causes of accidents and incidents (i.e. causal factors).

This chapter is organised in nine sections. The first derives the data requirements from the findings of the previous chapters. The requirements are used in the second section to develop a data collection strategy. The third section discusses data availability and data collection methods. A summary of the collected data is given in the fourth section, and the quality assessment (validation) is dealt with in the fifth section. In particular, the data is analysed for its internal validity (i.e. precision), external validity (i.e. accuracy), and in terms of reporting levels. A novel external data validation framework is developed and each database is rated with a data quality index (DQI). The sixth section introduces the databases and describes data pre-processing. The seventh section presents the analysis of the data to determine causes of accidents and incidents, and the results are used to refine the initial taxonomy based on the literature. The ninth section concludes the chapter.

6.1 Data Requirements

Table 22 presents the requirements for safety data, derived from the findings of Chapters 2 to 5.

Table 22: Data requirements

Findings	Data requirements
Chapter 2 – Airport system	
• The implementation of the airport architecture is variable in regards to: - Physical infrastructure - Stakeholders - Stakeholder responsibilities (i.e. operations)	• Large variety of airports, including: - Airports of different size in terms of physical infrastructure and performance (e.g. movements, passenger boardings); - Representation of different national airport systems
Chapter 3 – Airport surface operations	
• Airport surface infrastructure is variable	• Representation of diverse airport surface infrastructures
• Coordination and interaction of multiple stakeholders on the airport surface • Dynamic behaviour of actors	• Data that contains the statements of all stakeholders directly (e.g. those involved) and indirectly (e.g. witnesses) involved in any occurrence
• Five main stakeholders are primarily involved in airport surface operations • Ground handling has the potential to infringe onto the airport surface	• Safety data from the main stakeholders: - Airport authorities - Airlines - Ground handling companies - ANSPs - Regulators
• Variability of stakeholder operations (e.g. seasonal requirements)	• Representation of different airport locations (i.e. landscapes) and external conditions (i.e. meteorological conditions)
• Surface operations can be affected by temporal effects	• Data covering at least three years of operations to establish trends
• Complexity of the airport surface and its operations (i.e. potential of failures within the process of normal operations)	• Collection of all occurrences (i.e. including occurrences with no direct safety impact)
Chapter 4 – Airport safety management	
• Importance of safety culture	• Data from countries and organisations known for a good safety culture to ensure a high quality of the data
Chapter 5 – Airport Safety Modelling	
• Focus of previous research on single occurrence types	• Data for all considered occurrence types (i.e. collisions / incursions, excursions, FOD, wildlife strikes)
• Consideration of single perspectives of aviation stakeholders in previous research	• Data representing the perspectives of all relevant aviation stakeholders

6.2 Data Selection

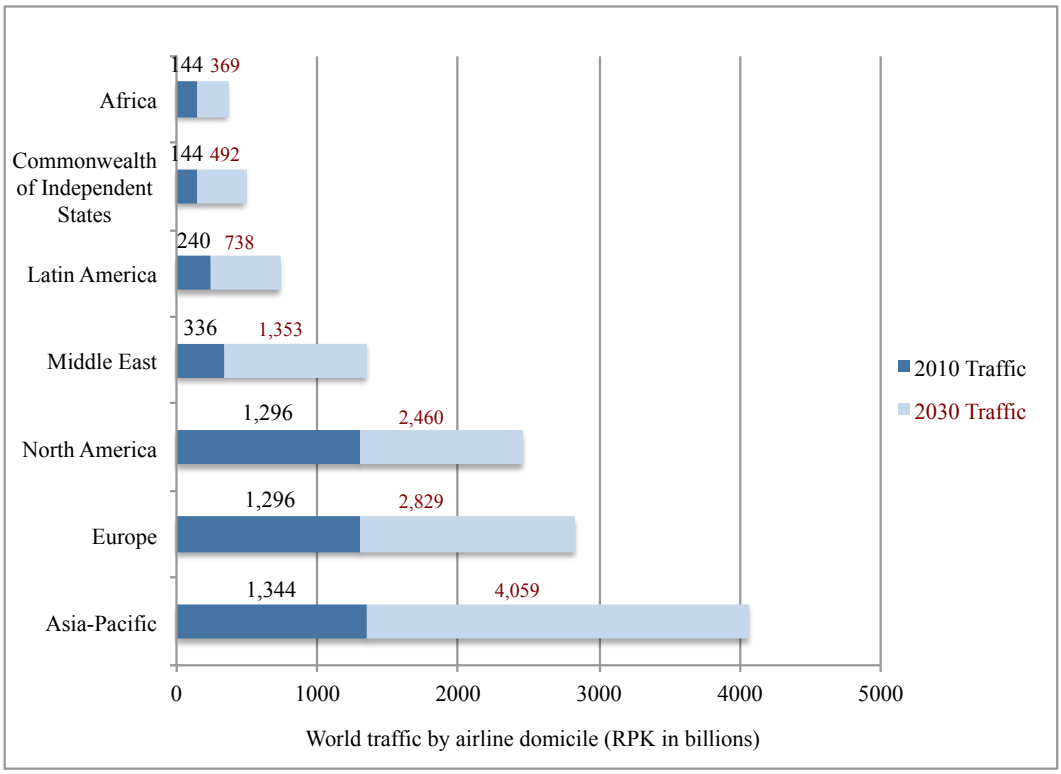
The highest priority for selecting safety data is quality. This is because of the direct relationship between statistical modelling accuracy and the quality of the data used. Research has shown that safety culture (defined as "the product of individual and group values, attitudes perceptions, competencies and patterns of behaviour that determine the commitment to and the style and proficiency of an organisation's health and safety management" (Advisory Committee on the Safety of Nuclear Installations, 1993)) is the basis for successful Safety Management Systems (SMS) (Choudhry, *et al.,* 2007). Therefore, countries and organisations with a good safety culture are also likely to be a good source of good quality data. In addition, the selected data should be representative in terms of global air traffic (i.e. traffic volume). The aim overall, therefore, is to identify relevant countries in terms of air traffic, known for a good safety culture, that fulfil the data requirements in Table 22.

6.2.1 Traffic Statistics

Figures 52 and 53 show the forecast for global air traffic from Airbus and Boeing respectively. Figure 52 shows the global market forecast and compares revenue passenger kilometres (RPK) for 2010 with the predicted RPK for 2030. The three dominant regions in 2010 are Asia-Pacific (28.0% of 2010 world RPK), followed by Europe and North America (both 27.0% of 2010 world RPK). A significant growth is predicted over the next 20 years (Airbus, 2011).

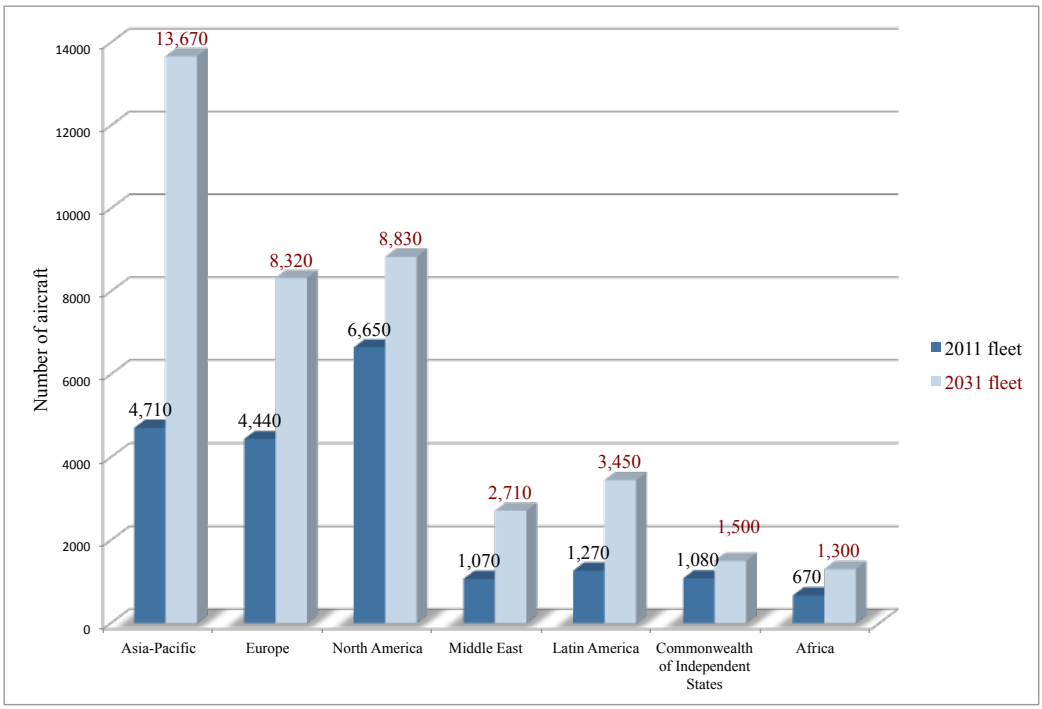
The forecast from Boeing in Figure 53 shows a prediction of the aircraft market for 2031 compared to 2011. In 2011 North America dominated the market with a fleet of 6,650 aircraft, followed by the Asia-Pacific region (fleet of 4,710) and Europe (fleet of 4,440). All three regions are predicted to experience a significant growth of at least 25.0%. North America's fleet is expected to increase by over 30.0%, Europe's to almost double, and the Asia-Pacific region to more than triple its fleet by 2031 (Boeing Commercial Airplanes, 2012a).

Both studies agree that the three dominant regions in terms of global air traffic are North America, Europe and Asia-Pacific, both currently and in the future. Hence, this research will focus on these three regions.



Source: Airbus (2011)

Figure 52: Global air traffic forecast 2010-2030 – revenue passenger kilometres



Source: Boeing Commercial Airplanes (2012a)

Figure 53: Global air traffic forecast 2011-2031 – aircraft fleets

6.2.2 Subject Matter Expert Consultation

In order to identify countries within North America, Europe and the Asia-Pacific region that are known in the aviation industry for a good safety culture, Subject Matter Experts (SMEs) from EUROCONTROL and the FAA were consulted. EUROCONTROL was chosen because of its commitment to ATM safety enhancements through its involvement in research and facilitation of safety related rule-making and formulation of regulations in European aviation. Similarly, the FAA is the regulatory body responsible to ensure safe and efficient operations in the U.S., the busiest country in terms of surface operations in North America. Senior experts in aviation safety with a minimum of 15 years of international experience were selected for consultation. The following experts were consulted:

- The FAA's Runway Safety Program Manager;
- EUROCONTROL's Head of Safety Unit;
- EUROCONTROL's Head of Safety Regulation (retired);
- EUROCONTROL's Senior Safety Expert.

The initial consultation resulted in inclusion of the United States in the analysis. This is because the U.S. accounted for 787 billion revenue passenger miles (RPM) (≅ 1,266 billion RPK) in 2010 (Federal Aviation Administration, 2011e) to form the largest air traffic market in North America. In addition, the FAA actively promotes safety.

Furthermore, in Europe, Scandinavian countries were in particular recommended for their safety culture and efforts to promote reporting. In addition, the consultation determined that Asian data should be excluded since most Asian countries still execute a punitive culture, i.e. a culture in which "those involved in occurrences are fearful of management or regulatory authority" (International Civil Aviation Organization, 2008). It was advised to include Oceania, which promotes a positive safety culture, instead (Structured communication with EUROCONTROL Head of Safety Unit, 2010; EUROCONTROL Senior Safety Expert, March 2010; FAA Runway Safety Program Manager, January 2010; Retired EUROCONTROL Head of Safety Regulation, December 2009). This was confirmed by the Assistant Director of one of Asia's major airports[3], pointing out that the punitive culture leads to incorrect reporting (Structured communication with the Assistant Director of one of Asia's Top 10 airports, June 2010).

[3] In 2012, the airport was among the top 10 busiest airports in Asia by passenger traffic per year

Based on the consultation results, and the focus on good quality data, this thesis excludes the Asian market despite its significance in terms of global air traffic. Clearly, future research should include Asia once the concept of a just culture has been established in this region.

6.2.3 Matching the Data Requirements

This section uses the data requirements in Table 22 and the results of the consultation of SMEs to select the case studies used in this thesis. An assessment of countries in North America, Europe, and Oceania led to the selection of four countries: United States (U.S.), United Kingdom (UK), Norway (NO), and New Zealand (NZ).

6.2.3.1 United States

The U.S. is a vast country that encompasses an area of almost 10 million km^2 and is the home of more than 314 million people. The national air traffic system is characterised by diverse airport infrastructures, including (Federal Aviation Administration, 2009b):

- Large hubs: airports with 1.0% or more passenger boardings,
- Primary nonhubs: airports with more than 10,000 but less than 0.05% annual passenger boardings,
- Nonprimary nonhubs: airports with at least 2,500 and no more than 10,000 annual boardings, and
- Reliever airports designated by the FAA to relieve congestion at commercial service airports and to provide improved general aviation access to the overall community.

The U.S. handles a mix of international and domestic (i.e. regional) traffic. Its airspace is a combination of very high traffic density (e.g. New England[4] with major hubs receiving traffic from Europe and distributing it into the mainland) and less busy areas (e.g. Northwest Mountain Region[5]). In addition, the U.S.'s geography is highly variable,

[4] New England comprises the states of Connecticut (CT), Maine (ME), Massachusetts (MA), New Hampshire (NH), Rhode Island (RI), and Vermont (VT) (Federal Aviation Administration, 2000)
[5] The Northwest Mountain Region comprises Colorado (CO), Idaho (ID), Montana (MT), Oregon (OR), Utah (UT), Washington (WA), and Wyoming (WY) (Federal Aviation Administration, 2000)

including mountain ranges in the west, prairies and farmland in the central parts, deserts in the south, and coastal areas. Similarly variable is its mix of climate zones, ranging from subtropical, or midaltitude desert climates, to alpine and polar climates (United States Census Bureau, 2012a, b; United States of America Central Intelligence Agency, 2012c).

6.2.3.2 United Kingdom

In Europe, the UK spans an area of some 243,000 km^2 and has a population of around 62 million people (Commonwealth Secretariat, 2010). The UK combines very dense airspace (e.g. London Terminal Area), with medium-sized nonhub airports (e.g. Birmingham) and smaller regional airports (e.g. Southampton). According to Eurostat, the UK handled 198,532,000 air passengers in 2009. This makes the UK the busiest country in Europe (in terms of air passengers) followed by Germany (158,150,000), Spain (148,318,000), and France (117,557,000) (European Comission, 2011). In addition, London Heathrow is the busiest airport in Europe with 69,433,230 passengers handled in 2011 (Airports Council International, 2012). The country's landscape ranges from uphill to lowlands and coastland. The maritime climate is influenced by the Atlantic ocean and Gulf Stream (Commonwealth Secretariat, 2010).

6.2.3.3 Norway

As Europe is fragmented in many countries, two case studies were chosen to represent this region. Norway is characterised by diverse population centres and large distances between these centres. It spans an area of about 325,000 km^2 and has a population of five million people (Statistisk sentralbyra, 2012). It is part of Scandinavia and is characterised by a long and rugged coastline with numerous fjords and small islands. Mountainous terrain and valleys in the lowlands dominate large parts of the country. Norway spans several climate zones ranging from temperate, alpine and arctic in the north and on the mountains, to a continental and coastal climate. Because of Norway's high latitude there are large seasonal variations in daylight (i.e. in summer the sun does not descend beneath the horizon and in winter it does not rise above the horizon in the areas north of the Arctic Circle) (Statistisk sentralbyra, 2012; United States of America Central Intelligence Agency, 2012b). Norway's only hub airport is Oslo although, in addition, it has three

medium-sized airport[6] (Bergen, Trondheim and Stavanger) and a variety of small regional airports. Due to the terrain and meteorological conditions, in certain areas, air transport is the only means of transportation possible.

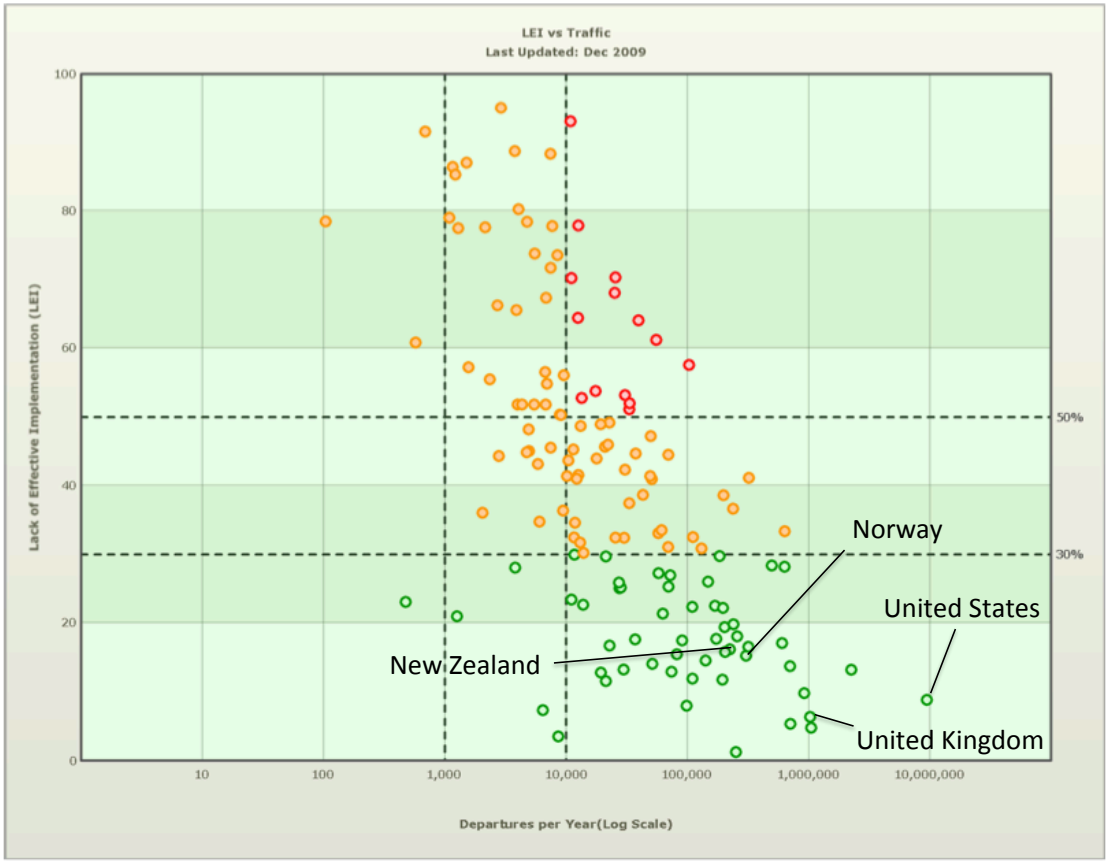
6.2.3.4 New Zealand

New Zealand ranges over 268,000 km^2 and has a population of around 4.4 million. It consists of two main islands and a large number of smaller ones. The country has a varied topography including glaciers and fjords, mountains, tropical forests and coastline (United States of America Central Intelligence Agency, 2012a). Its airport infrastructure is characterised by a combination of three main airports (two hubs: Auckland and Christchurch, and a major nonhub: Wellington) and a large number of very small regional airports. It is typified by a mild and temperate maritime climate.

6.2.3.5 Data Choice and Quality

The selected sample of countries allows for the comparison of different operations in different countries with diverse underlying air traffic movement characteristics and topographies. To validate the quality of data likely to be derived from this choice of countries, the ICAO's Lack of Effective Implementation indicator (LEI) is used. LEI is a compliance measure of a state's safety oversight capabilities. Figure 54 shows the LEI against the traffic volume for all States audited under ICAO's Universal Safety Oversight Audit Programme (USOAP). A LEI percentage under 30.0% corresponds to the most favourable USOAP result (International Civil Aviation Organization, 2009c). The four countries selected for this research meet this criterion, each having a LEI below 20.0%.

[6] Between 57,912 and 103,183 annual civil aircraft movements (Avinor AS, 2012a)



Most favourable – includes States having LEIs of 30.0% or below
Moderate – includes States having LEIs between 30.0% and 50.0%
Least favourable – includes States having LEI above 50.0%

Source: International Civil Aviation Organization (2009c)

Figure 54: Lack of effective implementation indicator vs. traffic

6.3 Data Availability and Collection

In order to achieve the goal of an integrated management of surface safety, a data requirement is the representation of all the relevant stakeholders in each country (airport authority, airline, ground handling company, ANSP and regulator). This section discusses the national data collection systems of the four chosen countries, data availability, and the efforts made to collect the required data. As in Chapter 3, V/PD are considered in the form of the airport authority and ground handling.

6.3.1 United States

In the U.S., there is no centralised database capturing all safety related occurrences. Instead, airport surface accident and incident types are captured in different databases at the regulatory level. Currently, the U.S. focuses on the mitigation of incursions and adopts associated data collection mechanisms. There is no regulatory requirement to report excursions and FOD occurrences, unless they meet the definition of an accident. Wildlife strike reporting is voluntary (Structured communication with FAA Runway Safety Office Analysts, August 2011). The lack of integrated safety databases and focus on single occurrence types corresponds to the limitations identified in the literature review as outlined in Chapter 5.

The FAA Runway Safety Office in Washington, D.C. keeps an internal database of incursions that is not publically available. The FAA is the regulatory body in the U.S. and provides in addition ATC services for 504 controlled airports (Federal Aviation Administration, 2008b). Hence, the incursion database reflects both, the regulatory and the ANSP viewpoint. The airport operators typically report incursions to the FAA and do not keep a separate database locally (Structured communication with Airfield Operations Manager Boston Logan International Airport; Airfield Operations Manager Manchester Boston Regional Airport, September 2011). Excursion and FOD data is publically available from the FAA's Accident / Incident Data System (AIDS). The FAA Wildlife Strike Database is likewise publically available. Airlines and ground handling companies keep their own safety databases.

The FAA was approached and the internal incursion database from the Runway Safety Office obtained. In addition, excursion and FOD data was downloaded from AIDS (Federal Aviation Administration, 2012a). Since wildlife strike reporting is voluntary in the U.S. it cannot be determined what percentage of wildlife strikes is represented in the Wildlife Strike Database. Hence, the results of any analysis may be significantly biased and it was therefore decided to exclude this data.

Airports typically do not keep their own databases and report into the FAA system, hence, their viewpoint is also reflected in the FAA databases. To obtain airline data two U.S.-based airlines were approached, but without success. The airlines, one of the top five in terms of passengers and a major low-cost carrier, were chosen because of their positive reputation for their safety efforts in the U.S. aviation industry (Structured communication

with Airfield Operations Manager Boston Logan International Airport, FAA Regional Runway Safety Manager, September 2011). Both stated that they do not share any safety-related data with third parties (Structured communication with two U.S.-based Airline Safety Managers, September 2011). This was confirmed through structured communications with the FAA, where senior safety experts confirmed that U.S. airlines do not share their internal safety databases (Structured communication with FAA Runway Safety Office Analysts, August 2011). To capture the viewpoint of U.S. pilots, interviews were conducted and the details are discussed in Chapter 7. Finally, a database from a ground handling company, Signature Flight Support (Signature), was obtained under a confidentiality agreement. Signature operates at 63 locations in the U.S. including large hubs and primary nonhubs and is therefore representative for the U.S. (Signature Flight Support, 2011).

6.3.2 United Kingdom

The UK's regulatory body, the UK Civil Aviation Authority (UK CAA), keeps a centralised database that captures all occurrence types. The ANSPs keep their own safety databases. A structured communication with a major UK airport authority revealed that, similar to the U.S., they do not keep their own safety databases. Occurrences are reported into the regulatory reporting system and no additional data could be obtained from the airport authority itself (Structured communication with Head of Policy Standards of a major UK airport authority, 2011). Airlines and ground handling companies maintain their own reporting systems.

The UKCAA was addressed and its data for all relevant occurrence types obtained under a confidentiality agreement. In addition, a major UK ANSP was approached, however, a confidentiality agreement could not be signed and therefore no data could be gathered and no interviews with their staff were allowed. Likewise in the U.S., the viewpoint of the approached major airport authority is reflected in the regulatory database. To capture the airline perspective, easyJet plc (easyJet) was approached and its data obtained under a confidentiality agreement. easyJet was chosen since it is known in the industry for its safety efforts. The search for ground handling data turned out to be difficult. Structured communications with two major handling companies revealed that

ground handling companies typically collect only data regarding occurrences on the apron (e.g. personal injuries, damage of property) (Structured communication with two Safety Managers of major ground handling companies in Europe, 2011). Occurrences that involve ground handling personnel on the manoeuvring area were said to be collected by the ANSP, the airline, or the airport operator, but would not be reported to the handler's database. Finally, access to the data of a U.S.-based ground handling company (Signature) was granted: since Signature operates worldwide, their database contains also occurrences from major UK airports.

6.3.3 Norway

In Norway each stakeholder keeps its own database capturing all occurrence types. Confidentiality agreements were signed and safety data obtained from the regulator (Civil Aviation Authority – Norway (CAA Norway)), the ANSP (Avinor AS – ANSP Division (Avinor ANSP)), the airport authority (Avinor AS – Airports Division (Avinor Airports)) and Oslo Lufthavn AS (OSL), as well as two airlines (Norwegian Airshuttle ASA (Norwegian) and Widerøe Flyveselskap AS (Widerøe)). According to the SMEs consulted from EUROCONTROL, all these organisations have an excellent reputation for their safety culture. In Norway, both ANSP and airport authority services are provided by Avinor. However, these are managed and operated by different divisions that maintain their own safety databases. Avinor's airports' division holds the safety data for the airports with one exception: Oslo Lufthavn. OSL is a privatised company and maintains its own safety data collection system. The search for ground handling data proved to be difficult, since ground handling typically does not collect data of occurrences on the manoeuvring area. In addition, due to language constraints interviews proved to be difficult. It was therefore decided to exclude the ground handling perspective, since the UK data allowed already an insight into European handling practices.

6.3.4 New Zealand

Similar to Norway, each stakeholder in New Zealand also collects its own safety data. Due to resource and time constraints it was not possible to address all the different stakeholders within the limits of this research. Nonetheless it was decided to provide an

overview on New Zealand's surface safety occurrences. To do so, the CAA was approached. The Civil Aviation Authority New Zealand (CAA NZ) was chosen because regulatory bodies typically comprise occurrence reports from all aviation stakeholders.

Table 23 summarises the data collection methods.

Table 23: Data availability and collection

Stakeholder	United States	United Kingdom	Norway	New Zealand
Regulator	Data	Data	Data	Data
ANSP	Data	-	Data	-
Airport authority	Data*	Data*	Data	-
Airline	Interviews	Data	Data	-
Ground Handling	Data	Data	-	-

* Data indirectly available over other stakeholders

6.4 Data Overview

Table 24 summarises the collected data. The dataset combines databases from all relevant stakeholders in the context of airport surface safety and, in addition, allows for multi-national comparisons. With these unique characteristics the collected data overcomes the limitations of previous research and serves as a reference data set for the statistical analyses in Chapters 7 to 11.

Table 24: Data overview

Database	Organisation	Stakeholder
United States		
FAA Runway Safety Office Runway Incursion (RI) Database (Federal Aviation Administration Runway Safety Office, 2010)	Federal Aviation Administration (FAA)	Regulator & ANSP
Accident / Incident Data System (AIDS) (Federal Aviation Administration, 2012a)	Federal Aviation Administration (FAA)	Regulator & ANSP
Safety, Health, Environment, BBA (SHEBBA) (Signature Flight Support, 2012)	Signature Flight Support (Signature)	Ground Handling
United Kingdom		
Mandatory Occurrence Reporting Scheme (MORS) (UK Civil Aviation Authority, 2011b)	UK Civil Aviation Authority (UK CAA)	Regulator
Aviation Safety Database (AQD) (easyJet plc, 2010b)	easyJet plc (easyjet)	Airline
Safety, Heath, Environment, BBA (SHEBBA) (Signature Flight Support, 2012)	Signature Flight Support (Signature)	Ground Handling
Norway		
European Coordination Centre for Accident and Incident Reporting Systems (ECCAIRS) (Civil Aviation Authority - Norway, 2011)	Civil Aviation Authority – Norway (CAA Norway)	Regulator
MessageSystem (MESYS) (Avinor AS - ANSP Division, 2011)	Avinor AS – ANSP Division (Avinor ANSP)	ANSP Division
MessageSystem (MESYS) (Avinor AS - Airports Division, 2011a, b)	Avinor AS – Airports Division (Avinor Airports)	Airports Division
Industrial and Financial Systems (IFS) Database (Oslo Lufthavn AS, 2011b)	Oslo Lufthavn AS (OSL)	Airport operator
Aviation Safety Database (AQD) (Norwegian Air Shuttle ASA, 2011a)	Norwegian Air Shuttle ASA (Norwegian)	Airline
Sentinel Safety Information Management System (Sentinel) (Widerøe Flyveselskap AS, 2012)	Widerøe Flyveselskap AS (Widerøe)	Airline
New Zealand		
Aviation Safety Monitoring System (ASMS) (Civil Aviation Authority of New Zealand, 2010a)	Civil Aviation Authority of New Zealand (CAA NZ)	Regulator

Before analysing this data, the following sections conduct a thorough data quality assessment.

6.5 Data Quality Assessment

The quality of data analysis and modelling is dependent on its inputs, i.e. the quality of the underlying data sets. In particular, when aggregating safety databases, differences in

data quality have to be addressed and corrected, since variable data quality has a negative impact on the risk assessment within an organisation (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2006). Three aspects of data quality should to be considered: external factors (i.e. how accurately does the database reflect occurrences), internal factors (i.e. how precise is the data), and the reporting level. This section assesses the quality of the safety data and the results are then used to decide whether the databases can be aggregated.

6.5.1 Data Quality Issues

Chapters 4 and 5 identified the factors that can affect the quality of safety data. The main limitations of the literature on data quality are:

- The scope of the collected data, i.e. which occurrence types are collected and by whom. The scope of the reporting system and different underlying definitions can lead to differences in the reporting level;
- The use of insufficient and ambiguous definitions;
- A lack of a reliable methodology for data analysis (e.g. coding). Data can be biased by the analysis that has been performed on it, e.g. through an inappropriate taxonomy used for data coding;
- In most cases, the relevant literature does not specify its data sources in enough detail to evaluate its quality;
- If data from different sources is aggregated, data quality is not taken into account;
- There is no information on the assessment of the data accuracy.

The impact of data quality is acknowledged in generic as well as aviation research. Research on the management of data quality in a variety of industries has identified numerous data quality dimensions, including relevance, completeness, consistency, interpretability, accuracy, timeliness and accessibility. These dimensions have been cited in various published studies relevant to the requirements of good data quality for generic systems or for statistical agencies (e.g. Lee*, et al.*, 2006; Wang and Strong, 1996).

A recent study by Dupuy (2012) addresses data quality issues for aviation safety databases by developing a framework for the analysis of loss of separation related incidents. Dupuy analyses five safety databases and develops a data quality assessment

framework in order to provide an indicator for the suitability of databases for certain types of analysis. Based on the analysis of incident data three reasons are highlighted that account for data quality concerns:

1. The reporting scheme, in particular the data collection process and reporting form;
2. The data coding process and the resulting database structure; and
3. The reporting level, which refers to two aspects. First, whether everything is reported and, second, the relevance and quality of the reported information.

A study by Van der Schaaf and Kanse (2004) addresses extensively the latter aspect of the reporting level. The authors look at the level of reported events involving recovery from self-made errors in a study with chemical plant operators, identifying six reasons for not reporting (e.g. afraid / ashamed, recovery, no learning).

In addition to the studies above, data quality issues have been discussed by a range of national and multinational organisations. The impact of a just culture on the reporting level is addressed for instance by the EUROCONTROL Data Reporting & Data Flow (SAFREP) task force (The European Organisation for the Safety of Air Navigation, 2008b).

The United States Government Accountability Office (GAO) has addressed problems with importing data from external data sources. The GAO pointed out the need to obtain information from various data sources, the need for standardisation to overcome data inconsistencies, and problems associated with data integration (e.g. translating data) and data loading (e.g. importing data) (United States Government Accountability Office, 2010).

The Commercial Aviation Safety Team / International Civil Aviation Organization (CAST/ICAO) Common Taxonomy Team acknowledges problems associated with aviation nomenclature (e.g. anomalies in definitions), in particular problems with analysing, integrating and sharing data from multiple sources systems. Problems such as duplicate or multiple entries are also associated with this (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2006). The integration of different data systems is further addressed by the Global Aviation Information Network (GAIN). GAIN considers data quality to be crucial when implementing data sharing systems and stresses the importance of completeness, consistency, validity and accuracy for data in such systems (Global Aviation Information Network, 2003).

The National Transportation Safety Board (NTSB) reviewed safety recommendations concerning data quality for transportation safety databases. The identified recommendations fall into five groups: the development of a new database to collect data that fits to a particular study scope; the modification of existing databases and or reporting forms; the improvement of data accuracy, currency, or completeness; addressing the problems of underreporting; and the improvement of data analysis and dissemination (National Transportation Safety Board, 2002).

The factors mentioned in the literature, as summarised above, can be classified into three categories. The first concerns factors relating to the reporting system and its quality (i.e. external factors). The second category relates to the quality of the data itself (i.e. internal factors). Finally, the importance of the reporting level has been stressed. The following sections propose a framework for a holistic data quality assessment that takes all three of these dimensions into account.

6.5.2 Definitions

Based on the discussion in the section above this research assumes the following definitions:

External data validation refers to accuracy, i.e. how accurately the data reflects the truth of what happened, or how accurately the reporting and investigation process captures any occurrence.

Internal data validation refers to precision, i.e. whether a database has been constructed and pre-processed consistently.

The *reporting level* is determined by the reporting scope, the underlying definitions for accident and incident types, and the consistency of the reporting system, i.e. whether the reporting scope and definitions changed over time.

6.5.3 Data Quality Assessment in Aviation Research

Although acknowledged in aviation research, previous models for aviation safety fail to account for data quality issues. This section focuses particularly on EUROCONTROL's IRP and NLR's CATS, both of which were discussed in the literature review as models which quantify the risk of aviation occurrences. IRP represents the risk of aviation accidents with a particular emphasis on ATM contributions, whereas CATS quantifies the risk for 33 separate accident scenarios. The IRP makes use of a total of 137 worldwide accidents involving large Western commercial jets between 1990 and 2002 as well as a selection of incidents involving commercial aircraft between 1998 and 2004 (The European Organisation for the Safety of Air Navigation Experimental Centre, 2006). NLR's model, meanwhile, is based on Airclaims and ICAO's Accident / Incident Data Reporting (ADREP) system accident data between 1990 and 2003. In addition, original accident investigation reports and other data sources (e.g. Flight Safety Foundation) as well as incident reports have also been used where available (Ale*, et al.*, 2009).

Both models, CATS and IRP, take accident and incident reports into account. As introduced in Chapter 4, ICAO Annex 13 requires States to report "information on all aircraft accidents which involve aircraft of a maximum certificated take-off mass of over 2,250 kg" (International Civil Aviation Organization, Year not specified). However, "there is no obligation for States to conduct an investigation into an incident" (International Civil Aviation Organization, Year not specified). The extent to which incidents are reported is therefore up to the individual aviation stakeholders. This implies that both the rates of incidents and the quality of incident reports may vary significantly and, therefore, a data quality assessment is particularly important when working with incident data and when combining data from different sources. In this respect, while both models aggregate multi-national data from different sources, they do not account for differences in data quality.

6.5.4 Data Validation Framework

To address the importance of data quality, this section develops a data validation framework in three steps. The objective is to identify differences in data quality between the databases. The data quality assessment framework by Dupuy (2012) considers the four metrics of relevance, completeness, consistency and accessibility. Thus, it allows

assessment of the quality of the data itself (i.e. internal validation). Factors related to 'trust' (whether the data reflects the truth of what happened) are excluded.

Dupuy's framework for internal data validation is applied and the need for an external data validation framework justified. A novel external data validation framework is subsequently proposed, which assigns a data quality index (DQI) to each database. Finally, reporting levels are analysed, prior to the conclusion of whether airport surface safety data can be aggregated. Figure 55 outlines the high-level methodology.

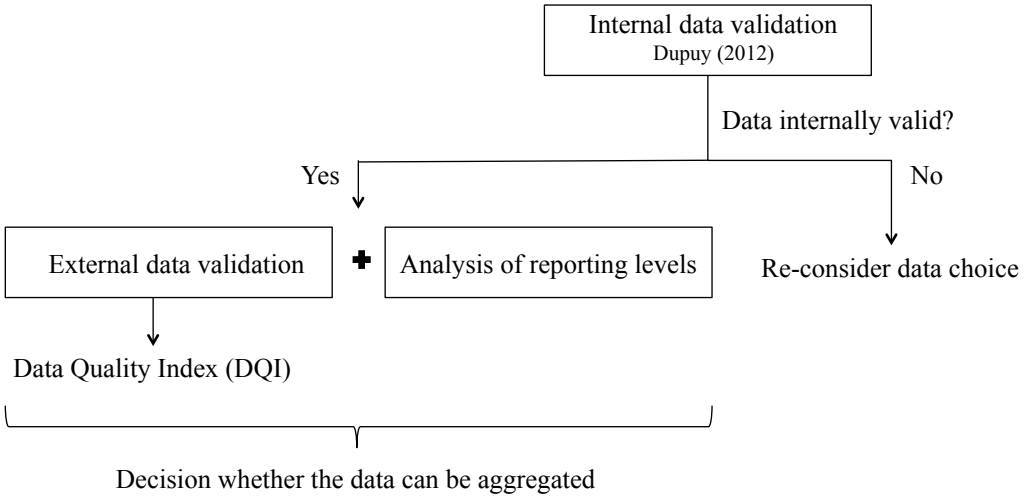


Figure 55: High-level methodology data quality assessment

6.5.4.1 Internal Data Validation

Internal validation refers to precision and does not challenge the accuracy of the data (i.e. whether the data reflects the truth of what happened during an occurrence); rather it evaluates the quality of the data set for subsequent analysis. Internal validation assesses whether the data is good enough for statistical analysis and ultimately whether any statistical model based upon the data can predict the data well.

The following paragraphs check the twelve databases for internal validity using Dupuy's framework (Dupuy, 2012).

- **Relevance**

Relevance refers to the extent to which information is applicable for the task at hand. It refers to the question of how many data fields within a database are relevant for the

anticipated analysis. Relevance is measured as the ratio of available variables (i.e. total number of variables in a database) to required variables (i.e. data fields useful for the anticipated analysis) (Dupuy, 2012).

The relevance criterion is useful when assessing the quality of a whole database for a certain type of analysis. For the purpose of this research specific information on surface safety occurrences was requested from the organisations. Thus, most datasets include only information relevant to this research (e.g. date, location, descriptive narrative). Only Avinor ANSP, Avinor Airports Division, and OSL provided their full databases with additional information.

An assessment for relevance would be biased as the data providers were not asked for their full databases. In addition, the relevance of data fields is not of particular interest, as this research is not trying to assess which analysis could be done with a database. This research analyses the descriptive narrative of accident / incident reports and develops a model of airport surface safety based upon it. Hence, it is more important to assess the relevance and quality of information given in the narratives. To do so, the quality of the underlying reporting system needs to be evaluated.

- **Completeness**

Data completeness is directly related to the quantity of reported variable values for each required data field. It is an indicator of the presence of missing values and is measured as the ratio of missing values per required variables (Dupuy, 2012).

Three variables are important in the context of this research: occurrence date, occurrence location (airport), and the descriptive narrative to extract the causal factors. The term descriptive narrative refers to the text that describes the occurrence, which can originate from different sources (e.g. reporter, investigator, analyst). The completeness score (1) is calculated as follows:

Completeness = 100 - arithmetic average of percentage of missing values per variable (1)

Table 25 summarises the results of the completeness assessment for the twelve safety databases.

Table 25: Completeness of relevant data fields within the occurrence databases

Database	Missing data 'Date'	Missing data 'Location'	Missing data 'Descriptive narrative'	Overall completeness indicator
FAA RI database	0.0%	0.0%	0.0%	100.0%
FAA AIDS	0.0%	2.1%	0.0%	99.3%
Signature SHEBBA	0.0%	0.0%	0.0%	100.0%
UK CAA MORS	0.0%	0.0%	0.0%	100.0%
easyjet AQD	0.0%	0.0%	0.0%	100.0%
CAA Norway ECCAIRS	0.0%	0.0%	0.0%	100.0%
Avinor ANSP MESYS	0.0%	0.0%	0.0%	100.0%
Avinor Airports MESYS	0.0%	0.0%	0.0%	100.0%
OSL IFS	0.0%	0.0%	0.0%	100.0%
Norwegian A/S AQD	0.0%	0.0%	0.0%	100.0%
Wideroe Sentinel	0.0%	0.0%	0.0%	100.0%
CAA NZ ASMS	0.0%	0.0%	0.0%	100.0%

The completeness indicator shows 100.0% completeness for eleven databases. Only the FAA AIDS database lacks information concerning the location in 2.1%of cases. A descriptive narrative was available for all occurrence reports. Therefore, all databases are evaluated as internally complete. However, in practice, when reading the descriptive narratives of the different databases, differences become apparent. Some databases, such as the FAA RI database, seem to contain high-level descriptions of the occurrences, whereas other databases (e.g. airlines) contain more detail as to why an accident / incident occurred. Thus, a simple analysis of the existence of a narrative is insufficient. It is more important to assess the quality of the narrative, i.e. whether the description is sufficient to describe what really happened. For these reasons external data validation is needed.

- **Consistency**

Data consistency evaluates whether variable values are coherent and compatible with one another within their corresponding data field. The principle of consistency is used to assess the quality of categorical and numerical data. Consistent data is presented in the same format and is compatible with previous data. Consistency can be evaluated based on the extent to which the original taxonomy / scale used to create a categorical / numerical variable is sufficient. When a fixed number of descriptors is applied to a categorical variable over time, or a numerical variable applies a consistent measure (e.g. scale) the variable is evaluated as 'consistent'. When the number of categories is underdetermined and / or the values within one variable are not consistent with one another, a variable is

rated as ‘inconsistent’. This can be the case, for instance, when descriptors are added over the course of time in circumstances where the underlying taxonomy has proved insufficient. In addition, it is possible that some data fields lack coding (Dupuy, 2012).

This research is based on an analysis of the descriptive narrative of occurrences for causal factors. This analysis is done by the researcher for each of the databases according to the same principles, and hence can be evaluated as consistent. The details on data coding will be introduced in section 6.7. In the context of this research it is in addition important to consider the consistency of the underlying data, e.g. whether the reporting system, and hence the way of collecting the data, changed over time (e.g. underlying definitions), but this is a matter of external validation.

- **Accessibility**

Data accessibility refers to the ease with which the data is obtained. Data can be explicitly, implicitly, or it may be inferred. Explicit data refers to data that is provided in its final format and is directly accessible in the database (e.g. date, location). Implicit data refers to data values that can be derived from another data field or in the descriptive narrative (e.g. causal factors extracted through analysis of the descriptive narrative). Inferred data values are derived or computed from other reported data values (e.g. the phase of flight can be deduced from issued clearance details) (Dupuy, 2012).

This research is based on implicit data, i.e. the extraction of causal factors from the descriptive narrative. This is the case for all of the twelve databases. Thus, there is no difference in internal accessibility, and hence quality, between the databases.

Accessibility is also an important aspect of external validation, however. The accessibility of different parts of the reporting system (e.g. original report, investigation findings, analyst’s summary) is important when inferring the external quality of the data. For instance, if the researcher only has access to a secondary source summary, quality information might have got lost during the course of data collection. In addition, it cannot be verified whether this summary conforms to the original report.

- **Discussion**

In conclusion, the twelve databases are evaluated as internally valid. However, this research is heavily reliant on textual information (i.e. descriptive narrative). In this context, it has been shown that it is more important to assess the external quality of the data, i.e. whether the data reflects the truth of what happened. The following section proposes a novel external data validation framework and derives a DQI reflecting differences in quality of the underlying reporting systems.

6.5.4.2 External Data Validation

External validation refers to accuracy, i.e. how close is the data to the truth, or how accurately does the data collection and investigation process (reporting system) capture any occurrence. In order to validate the reporting systems underlying the twelve considered databases an external data validation framework is proposed.

Methodology

The proposed external data validation framework is based on Multi-Criteria Decision Analysis (MCDA), which is a technique that supports decision making by simplifying complex problems with several options assessed on multiple criteria. Different options (alternatives) are evaluated as possible solutions. Depending on the decision problem and objective of the study different types of solutions may be required. Some decision problems need to identify the best option (choice), or classify alternatives into groups (classification). Other problem situations require a ranking of options (ranking) or a simple description (description). The options are assessed on criteria, i.e. attributes against which the alternatives will be measured. These criteria may have different impacts (weights) to the solution (Koen, 2008).

MCDA follows an 8-step process (Garoufalia, 2007; Hwang and Yoon, 1981):

1) Definition of the decision context (study objective);
2) Identification of options;
3) Identification of criteria on which the options will be assessed;
4) Scoring of the options on the criteria;
5) Weighting of criteria according to their relative importance to the decision;

6) Aggregation of scores and weights;
7) Examination of results; and
8) Sensitivity analysis.

Different MCDA techniques are available but all follow this 8-step process. However, the techniques differ in their aggregation method. Different techniques are also available for scoring and weighting. The choice of a technique is dependent on the data input, the underlying assumptions and the required output.

- **Definition of the decision context (study objective)**

The objective is to weight safety databases representing the viewpoints of all relevant aviation stakeholders in the context of airport surface safety based on the quality of their underlying data collection and investigation processes.

- **Identification of options**

This research considers twelve safety databases (i.e. options).

- **Identification of criteria**

Step 3 refers to the identification of criteria by which the twelve options will be evaluated. A review of the subject matter literature did not reveal criteria that define the quality of the data collection and investigation processes.

In order to derive the criteria by which to assess the options, an ideal data collection and investigation process has been modelled, based upon an understanding of reporting systems and official ICAO documentation (e.g. International Civil Aviation Organization, 2005d, 2009e). The ideal reporting system was validated with a senior safety expert from EUROCONTROL (Retired Head of Safety Regulation) who assessed its attributes in a systematic manner and commented on their validity.

a. In an ideal reporting system, any occurrence, including low severity incidents or occurrences with no safety impact, are reported immediately after the accident / incident occurred.

b. The occurrence should be reported by multiple parties, i.e. by every person directly involved in the accident / incident or witnesses of the occurrence.
c. Reports are made using an electronic reporting form that feeds any report directly into a primary database. Once the occurrence report is submitted, it is pre-processed by a safety analyst, who undertakes a high-level analysis of the occurrence and assigns an appropriate investigator. Every accident / incident report is investigated using various methods (e.g. documentation, interviews, simulations), depending on the severity of the occurrence.
d. The investigation will identify the cause and hazards that led to the accident / incident. The investigation results are used to develop recommendations for safety actions in order to mitigate or eliminate risk factors. Recommendations and actions are followed-up regularly until completion.
e. Results of any investigation and the subsequent recommendations are fed back to those that reported it.
f. All data is stored in a primary database and used on an aggregated level for data analysis. Data analysis results are used to develop safety recommendations and actions to improve or eliminate risk factors. Safety statistics are published and shared within the organisational safety department, the management, the whole organisation, external aviation stakeholders, and the public. The database itself is shared with other aviation stakeholders.
g. An ideal reporting system assumes no bias (e.g. reporter bias, investigator bias) and that no errors are made.
h. The data collection and investigation process is consistent over time.

Eleven criteria for assessing the quality of organisational databases could be derived from the ideal reporting system. The criteria account for factors in relation to possible error sources during data gathering (e.g. timeliness of report, level of investigation) and data pre-processing (e.g. form of reporting and data pre-processing), organisational safety culture (e.g. safety publications, data sharing), data accessibility (database type, source of descriptive narrative), and the consistency of the reporting system over time. These criteria are summarised in Table 26. The chosen criteria are not an exhaustive list of the factors affecting the quality of reporting systems. Indeed, the quality of safety data can be influenced by various moderating and confounding effects (e.g. size of the organisation and available staff for accident / incident reporting and investigation, cost-benefits).

Criteria relating to the reporting level are not considered at this stage, since the proposed external data validation framework aims to assess the quality of the collected data rather than its amount. Data quality issues in relation to the reporting level are discussed subsequently.

Table 26: Criteria scores

Criteria	**Possible outcome**	**Score**
Time of report	On the day of occurrence	Percentage of occurrences reported on the day of occurrence
	Later / Unknown	0
Major form of reporting	Electronic reporting system	1
	Mixed: electronic reporting system & email, post, telephone	0.5
	Email, post, telephone	0
Level of investigation	All occurrences	1
	Most occurrences (>20 / year)	0.67
	Less than 20 / year (only high-severity occurrences)	0.33
	None	0
Bias [a]	No bias	1
	1 type of bias	0.86
	2 types of bias	0.71
	3 types of bias	0.57
	4 types of bias	0.43
	5 types of bias	0.29
	6 types of bias	0.14
	All 7 types of bias	0
Database translation required [b]	No	1
	Yes	0
Feedback given to the reporter	Yes	1
	No	0
Publication of statistics / safety reports [c]	All 5 types of publications	1
	4 types of publications	0.8
	3 types of publications	0.6
	2 types of publications	0.4
	1 type of publication	0.2
	None	0
Data sharing with other stakeholders apart from regulatory requirements	Yes	1
	No	0
Data accessibility	Original report	1
	Primary database	0.75
	Report written by the primary organisation	0.5
	Secondary database	0.25
	Tertiary database	0
Source of descriptive narrative	Reporter + primary investigator	1
	Reporter + primary analyst	0.875
	Reporter + secondary investigator	0.75
	Reporter + secondary analyst	0.625
	Primary investigator	0.5
	Primary analyst	0.375
	Secondary investigator	0.25
	Secondary analyst	0.125
	No narrative	0
Consistency of the reporting system over time	Consistent	1
	Inconsistent	0

[a] Seven types of bias are considered: reporter bias, reporting form bias, analysts / commenter bias, investigator bias, and database bias. Analyst / commenter bias and investigator bias may occur twice in secondary systems. For instance, investigator bias may occur in the primary organisation. Investigation findings are then transferred to a secondary organisation, which may decide to investigate the occurrence again.
[b] Certain databases require a translation into English language by the analyst.
[c] Five types of publications are considered: publication to the organisational safety department, Board / Management, whole organisation, other aviation stakeholders, and the public.

- **Scoring of the options on the criteria**

After evaluation criteria have been identified, the options are scored against the criteria. The most common method is direct scoring using relative preference scales. The most preferred option (best option) is identified and assigned a weight of 1. Similarly, the least preferred option (worst option) is identified and weighted 0. The remaining options are scored in between 0 and 1 based on their importance in relation to the best and worst option (Hwang and Yoon, 1981).

The scoring of options based on the best and worst reporting system implies that the options are scored in relation to each other. However, to establish meaningful weights the reporting systems should be scored in relation to an ideal system and a non-ideal system. In this case, 1 is assigned to the ideal system and 0 to the non-ideal system. Subsequently, the twelve databases are scored in between 1 and 0 with reference to the ideal and non-ideal system. For this purpose, two new reporting systems, an ideal and a non-ideal system, are introduced. The ideal reporting system equates to the system introduced in the previous section. A reporting system with an overall score of 0.9 would mean that the system is lacking 10.0% of quality compared to the ideal one in relation to the evaluated criteria.

The scales for the criteria have been defined based on the possible outcomes. Table 26 summarises the criteria, possible outcomes of the criteria and assigned scores. For example, the major form of reporting in an ideal case is electronic (weight: 1), since every report is fed directly into a database with no loss of information. On the contrary, some organisations receive reports e.g. by post or telephone. This form of reporting significantly impacts on the time of data pre-processing (e.g. reports are manually entered into the database). In addition, errors may occur due to bad handwriting, typing mistakes, and the transfer of incorrect or incomplete information, etc. (weight: 0). A mixed form of reporting is assigned a weight of 0.5. The underlying distribution of the weights is linear and the impacts of this are discussed further in the next section.

The relevant data has been collected using a survey methodology, in which the providers of the safety databases were interviewed. Interview partners were senior analysts and investigators in the safety departments of the organisations. A semi-structured interview approach was applied for seven organisations. The interviews covered a list of themes and questions related to the evaluation criteria. A semi-structured approach was chosen in order to allow for some degree of flexibility, since the different aviation stakeholders employ different data collection and investigation processes, meaning that it

was sometimes necessary to query certain details in depth (Saunders*, et al.*, 2007). For five organisations, the survey was conducted via email, with a follow-up email or telephone call to clarify unclear responses. Where available, official documentation was used to verify the information given (e.g. The European Parliament and the Council of the European Union, 2003; UK Civil Aviation Authority Safety Regulation Group, 2011). The interview questions are shown in Appendix III.

Based on the data collected through the survey, the reporting systems were scored against the criteria. An example of the logic of scoring for the databases is given below.

The FAA keeps two databases for runway / taxiway incursion occurrences. Once an incident occurs, a report is filed to the Air Traffic Quality Assurance (ATQA) database with most of reports received being from air traffic controllers. Depending on the nature of the incident, different people investigate, e.g. for pilot deviations the Flight Standards District Office investigates. The original report is kept in ATQA until any investigation is completed and then replaced by the investigation findings. The data collection and investigation in ATQA is a primary process.

Each day, an analyst in the FAA Washington Operations Centre (WOC) compiles a list of incursion occurrences, called the Administrator's Daily Alert Bulletin (ADAB). The ADAB provides an overview of recent occurrences to FAA Executives. A safety analyst in the Runway Safety Office receives the ATQA and ADAB electronically (major form of reporting scoring: 1) and creates a new database. This secondary database is used in this research (data accessibility scoring: 0.25). Thus, the FAA Runway Safety Office is treated as a secondary organisation receiving their data from a primary process (i.e. ATQA data collection and investigation process). The database kept by the Runway Safety Office includes the times and locations of the occurrences and a summary of the incidents. This summary is written by the runway safety analyst (source of descriptive narrative scoring: 0.125), based on the original reports and investigation findings from ATQA and the daily bulletin ADAB. The database contains the day of occurrence, although no information as to when the incident was reported (time of report scoring: 0). The time between occurrence and reporting is important, as critical information can get lost (e.g. the reporter may not remember all details if the report is not made immediately). The runway safety analyst does a severity assessment. The Runway Safety Office does not investigate (level of investigation scoring: 0). The investigation was done through the primary process to which this research does not have access. The Runway Safety Office incursion database is used to produce monthly reports. In addition, the data feeds into a performance matrix to assess

whether organisational targets are met. All the statistics are available to other aviation stakeholders and the public (publications scoring: 1). In addition, the data is used for research purposes and ad-hoc safety mitigation actions. The Runway Safety Office does not give feedback to the person who reported the incident (feedback given to the reporter scoring: 0). The database itself is not shared with other aviation stakeholders (scoring: 0). The reporting system did not change over the considered time period (scoring: 1).

The scoring of the fourteen reporting systems is summarised in Table 27. Given that the ideal system is shown in Table 27 the table also highlights how an organisation could improve and make their reporting systems more comparable to an ideal system.

To validate the scoring, the agreement rate between two qualified raters is computed. Ideally, Cohen's Kappa inter-rater reliability should be calculated. This computes the extent of agreement between two raters, taking into account the possibility of the agreement occurring by chance. The scoring can be accepted as reliable if the agreement rate is at least 0.70. Cohen's Kappa needs to be computed for 25.0% of the data (Fleiss*, et al.*, 2003). Another qualified rater was asked to score 5 reporting systems. For this exercise, the five systems for which the data was received by email were chosen, since this allowed direct use of the written statements from the organisations. The agreement rate is 81.3% and the scoring is therefore evaluated as reliable. Inter-rater reliability could not be computed due to the small sample size and the heavily skewed distributions towards particular outcomes.

- **Weighting of criteria**

After the criteria have been defined and options scored on the criteria, they need to be rated according to their relative importance to the decision. A review of the relevant literature reveals no research on the quality of data collection and investigation processes. No justifications could be identified as to why particular criteria should have a higher weight than others. Therefore, weights cannot be derived from the literature. Weights could alternatively be derived using the input of SMEs, i.e. SMEs could be asked to weight the criteria. However, this has several problems. Firstly, although SMEs may be able to rank the criteria in relation to their importance, it could be difficult for them to assign quantitative values, as the aggregation of multi-organisational datasets accounting for data quality aspects has not been applied. This leads to the second problem, the choice of SMEs. SMEs for national databases and reporting systems exist, whilst experts with

experience in data quality concerning data aggregation are rare. In addition, such an approach is time and resource consuming, since a large number of relevant SMEs would need to be identified and addressed in order to derive robust weights.

The 'equal weights method' (Wang*, et al.*, 2009) is applied due to the lack of factual evidence on why weights should be assigned in a particular manner, as well as resource and time connected with a SME approach.

This method assumes an equal impact of the criteria on the final decision. Thus, the weight assigned to each criterion is 1. The implications of this decision will be discussed later in this section during the 'sensitivity analysis'.

- **Aggregation of scores and weights**

The choice of the aggregation method depends on the data input, the required data output, and the underlying assumptions. These can be defined as follows (Hwang and Yoon, 1981; Wang*, et al.*, 2009):

a) Data input:

- Qualitative data,
- Finite amount of options,
- Predefined set of options,
- No conflicting criteria,
- Independence of criteria;

b) Required output:

- Quantitative ranking of options,
- Solution for all options required;

c) Assumptions:

- Static preferences,
- No hierarchy of criteria and equal importance of all criteria,
- Compensation allowed (i.e. a bad score on one criterion can be compensated by a good score on another criterion),
- Certainty about the data input, i.e. it is assumed that all information given by the database providers regarding their underlying reporting systems is correct.

Based on these criteria, different MCDA methods were evaluated. The suitability of different MCDA methods to the current problem is summarised in Appendix IV.

The Weighted Sum Method (WSM), the most common approach in MCDA applications, was chosen as the most appropriate method. The overall value of an option s_i is calculated as a linear additive model as shown in equation (2)

$$s_i = \sum_{j=1}^{n} w_j x_{ij} \quad i = 1,2,\dots,m \tag{2}$$

where x_{ij} is the scoring of the i^{th} option on the j^{th} criterion and w_j the weight of the j^{th} criterion. After the overall scores for each option are calculated the values are normalised so that each value falls between 0 and 1. The absolute normalisation is calculated as outlined in equation (3).

$$s_{i\,normalized} = \frac{s_i - s_{MIN}}{s_{MAX} - s_{MIN}} \tag{3}$$

Table 27 contains the scoring of the twelve considered reporting systems on the criteria, the aggregated score, the DQI, and the final ranking.

Table 27: Scoring and ranking

Reporting system	Time of report	Major form of reporting	Level of investigation	Bias	Database translation required	Feedback given to the reporter	Publications of statistics / safety reports	Data sharing	Data accessibility	Source of descriptive narrative	Consistency of the report. system	Overall Score (WSM)	Normalized overall score (DQI)	Rank
UK CAA MORS	0	0.5	0.67	0	1	0	1	1	0.25	0.125	1	5.545	0.504	7
CAA NZ ASMS	0	0.5	1	0	1	0	0.8	0	0.25	0.25	1	4.8	0.436	9
CAA Norway ECCAIRS	0	1	0	0.14	0.5	0	1	0	0.25	0.625	1	4.515	0.410	11
FAA RI database	0	1	0	0.14	1	0	1	0	0.25	0.125	1	4.515	0.410	11
FAA AIDS	0	0.5	0	0	1	0	0	1	0	0.25	1	3.75	0.341	13
Signature Flight Support SHEBBA	0	1	0.67	0.29	1	1	0.4	0	0.75	0.875	1	6.985	0.635	5
Avinor ANSP MESYS	0.82	1	1	0.29	0	0	0.8	1	0.75	1	1	7.66	0.696	2
Avinor Airports MESYS	0.73	1	1	0.29	0	0	0.8	1	0.75	1	1	7.57	0.688	3
Oslo Lufthavn IFS	0.31	0	0.67	0.29	0	0	0.6	0	0.75	1	1	4.62	0.42	10
Norwegian A/S AQD	0.18	1	0.33	0.29	1	1	0.8	0	0.75	1	1	7.35	0.668	4
Widerøe Sentinel	0	1	0.33	0.29	0	1	0.6	0	0.75	1	1	5.97	0.543	6
Easyjet AQD	0	0	1	0.29	1	0	0.4	0	0.75	1	1	5.44	0.495	8
Ideal system	1	1	1	1	1	1	1	1	1	1	1	11	1	1
Non-ideal system	0	0	0	0	0	0	0	0	0	0	0	0	0	14

Sources: Avinor AS, 2011b, c; easyJet plc, 2009; Federal Aviation Administration, 2010c, 2011b, d, 2012a; Luftfartstilsynet, Accident Investigation Board Norway, 2010; National Transportation Safety Board, 2011; New Zealand Civil Aviation Authority, 2011; Norwegian, 2011; Oslo Lufthavn AS, 2011a; Structured communication with easyJet plc Safety Analysts and Investigatiors, July 2011; Structured communication with FAA Runway Safety Office Analysts, August 2011; Structured communication with Flight Safety Manager Norwegian, June 2011; Structured communication with Health Safety Environment Manager Signature, June 2012; Structured communication with Oslo Lufthavn AS Risk Manager, June 2011; Structured communication with Safety Analyst Avinor AS Airports, January 2012; Structured communication with Safety Analyst UK CAA, January 2012; Structured communication with Safety Department CAA NZ, December 2011; Structured communication with Safety Department Wideroe, June 2012; Structured communication with Safety Investigatiors Avinor AS ANSP, June 2011; Structured communication with Senior Advisor Analysis CAA-Norway, December 2011; The European Parliament and the Council of the European Union, 2003; UK Civil Aviation Authority Safety Regulation Group, 2002, 2011

- **Examination of results**

The overall ranking of the reporting systems in relation to an ideal system are shown in Figure 56.

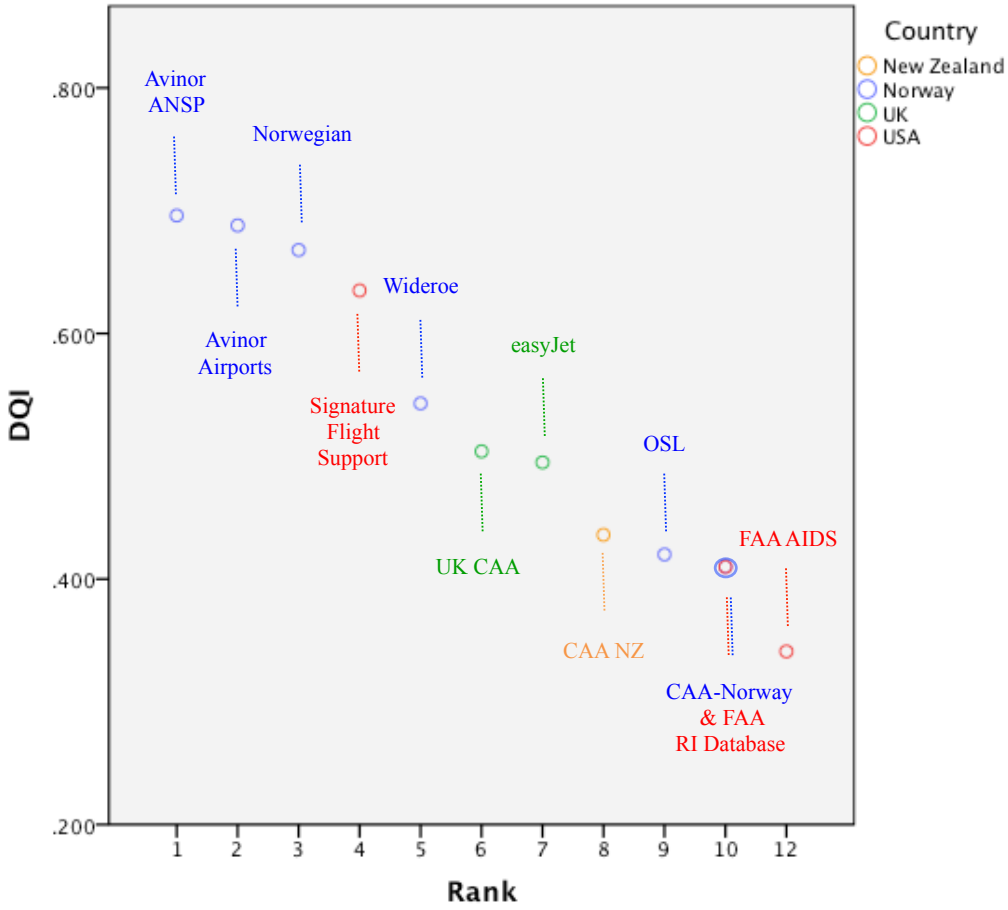


Figure 56: Final ranking

The data collection and investigation process of Avinor's ANSP Division scored highest with a DQI of 0.696, meaning that this reporting system lacks 30.4% of quality compared to an ideal system in relation to the evaluated criteria. The lack of quality results from possible biases, the translation of the data required by the analyst into the English language and the lack of a feedback process to the original reporter.

The lowest ranked is the FAA's AIDS database with a DQI of 0.341, which results mainly from the fact that AIDS is not a primary data collection system but a tertiary database that compiles occurrence reports from secondary databases. Original reports as well as analyses and investigation findings from the primary organisations are inaccessible.

AIDS contains a high possibility of bias because multiple organisations are involved in the data collection and investigation process. The data is publically available but is not used for statistics or safety promotion actions.

The ranking, as shown in Table 27 and Figure 56, highlights that the quality of regulatory data collection and investigation processes tends to be lower than that of the primary systems. Primary systems are ranked higher due to better data accessibility (e.g. primary databases), the source of the descriptive narrative being at the beginning of the data collection process (e.g. access to the original report), and less potential of bias since the data collection is completed within one organisation. A lower weight may not be important for the regulators themselves, however. Most regulators execute only a monitoring function (e.g. Norway) and the data they keep is good enough for this purpose. Due to the limited number of cases, no conclusions can be drawn as to whether a certain stakeholder (ANSPs, airport operators, airlines, ground handling companies) performs better among the primary organisations.

The final ranking shows a tendency of reporting systems from the same country to be ranked closely together (e.g. rank 1-3: Avinor ANSP Division, Avinor Airports Division, Norwegian; rank 6-7: UK CAA, easyJet; rank 10 and 12: FAA Runway Incursion Database, FAA AIDS). However, this is not due to similarities in the scoring, since the options score differently among the criteria. Possible explanations could be the overall safety culture of a country or its history, i.e. how systems are set up within a particular country.

- **Sensitivity analysis**

The derived weights and rankings are sensitive to the scoring of the options for each criterion and thus to the data collected through the stakeholder survey (i.e. interviews). The assumption of certainty about the data input (data collection and investigation processes) is vital and hence comprises the main limitation. This research uses the data collection and investigation processes to validate the quality of safety data. Future research should validate the reporting systems, i.e. to assess whether the information gathered through the SME survey is valid.

Furthermore, the weights and rankings are sensitive to the weights assigned to each criterion. Since an external data validation framework is a novel approach, this study did not consider weights due to the lack of factual evidence and access to appropriate SMEs.

Ideally the criteria should be modelled in a hierarchical manner and weighted according to their relative importance to the overall decision. Weighting of the criteria may result in a change in the overall scores for each of the options and in the subsequent ranking.

Finally, the definition of an ideal and non-ideal system and the derived scales used during scoring influence the overall scores of the options. In order to check for accuracy, the ideal and non-ideal systems and scales were validated with an independent SME from EUROCONTROL (Retired Head of Safety Regulations). The SME had more than 20 years experience in aviation safety. In addition, linear scales were assumed for the criteria. In reality, the scales may have another form (e.g. exponential). For instance, the quality of narratives may not degrade linearly from the original report to the narratives given in secondary or primary databases. Future research should address the underlying distributions of the scales.

Application

To understand better the practical application of the DQI, the developed index was correlated to the causal factors extracted from each of the databases (the details of this extraction process are discussed in section 6.7, later in this chapter).

For this correlation the data was first checked for normality using the Shapiro-Wilk test for samples smaller than 50. The data proved to be significantly different from a normal distribution ($p < .05$) and therefore non-parametric techniques were required. To test the data for correlations between the DQI and the causal factors Spearman's correlation coefficient (r_s), a standardized measure of the strength of relationship between two variables that does not rely on the assumptions of a parametric test, was applied. Spearman's test works by ranking the data points in ascending order and then applying the parametric Pearson's correlation coefficient (r), the standardized measure of the strength of relationship between two normal distributed variables, to those ranks. Pearson's correlation coefficient is computed by dividing the covariance of two variables (cov_{xy}) by the product of the standard deviation of these two variables ($s_x s_y$):

$$r = \frac{cov_{xy}}{s_x s_y} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{(N-1) s_x s_y} \qquad (4)$$

The covariance is calculated as the sum of the deviation of observed values (x_i) of one variable x from its mean value ($\bar{x}$) multiplied by the corresponding deviation of the

observed valued (y_i) of a second variable y from its mean ($\bar{y}$). To get the average value of the combined deviations for the two variables the sum of the multiplied deviations is divided by the number of observations (N-1). To standardise the covariance it is then divided by the product of the multiplied standard deviations ($s_x s_y$). Pearson's correlation coefficient can take on values between -1, which indicates a perfect negative correlation between two variables, and +1, which indicates that the two variables are perfectly positively correlated. A coefficient of 0 indicates no relationship between the variables (Field, 2009).

To test further whether the distribution of the DQI differs across stakeholders the Kruskal-Wallis test was applied. The Kruskal-Wallis procedure is a non-parametric test of whether more than two independent groups differ, and tests the null hypothesis that the distributions of DQIs across k experimental conditions (i.e. types of stakeholders) are the same. The Kruskal-Wallis is based on ranked data. The observations are first ranked and then sorted into groups. For each group, the sum of ranks (R_i) and the number of observations n_i is subsequently obtained. Once R_i and n_i have been calculated for each group, the test statistic, H, is computed as:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1) \qquad (5)$$

The null hypothesis (i.e. observations are the same across groups) can be accepted if the test statistic is not significant ($p > .05$). In case of a significant test statistic ($p < .05$) the null hypothesis can be rejected and the alternative hypothesis accepted (i.e. observations differ across categories) (Field, 2009).

Two scenarios were analysed. First, the DQI was correlated to the total number of causal factors extracted from each database, i.e. the overall number of different causal factors found in each data set. To account for differences in database size the number of different causal factors was normalised by the total number of incidents captured in each database.

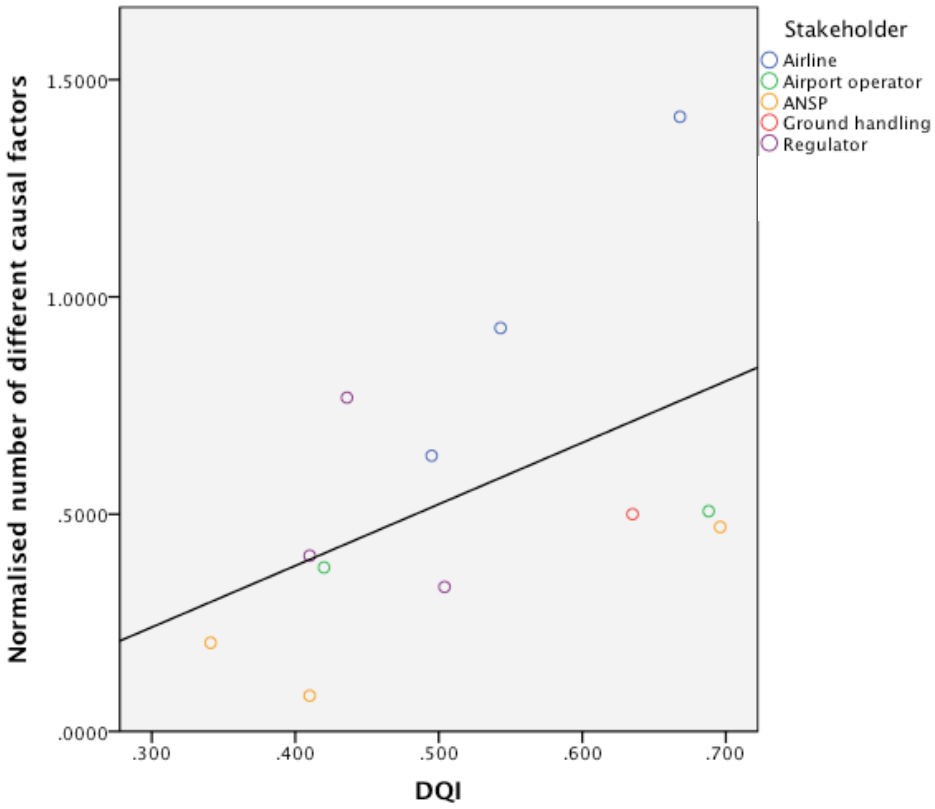


Figure 57: Correlation DQI vs. normalised number of different causal factors extracted per database

There is a relationship between the DQI and the normalised number of different causal factors extracted per database (r_s = .570, p < .05). Figure 57 illustrates this relationship graphically. The distribution of the DQI was the same across stakeholder categories (H(4) = .697, p > .05). The results indicate that databases with a higher DQI tend to capture causal factors in greater detail. There was no association between stakeholders and the DQI.

Subsequently, the DQI was correlated to the average number of causal factors extracted from each report. There was no relationship between the two variables (r_s = .522, p > .05). Also, the average number of causal factors extracted per report did not differ across the categories of stakeholders (H(4) = .474, p > 0.5). The results suggest that the DQI is not associated with the number of causal factors that can be extracted for each report. A possible explanation for this is that the number of causal factors extracted for each report is associated with the occurrence types collected by each of the stakeholders. The next chapter will analyse and quantify the relationships between stakeholders, occurrence types, and underlying causal factors in more detail.

Overall, the developed DQI is an indicator as to what extent a database captures the causal factors (i.e. the variety of causal factors) underlying airport surface safety occurrences.

The proposed external data quality assessment provides a robust indication of the quality of safety databases. A validation of the descriptive narrative itself is also possible through technical means. Automatic recording systems, such as airport ground radar tracks and voice recorders from aircraft and air traffic could be used to validate the accuracy of descriptive narratives. In this way, the different stakeholders could work together to provide a validation of occurrences. This would require considerable resources and coordination and future research should address both the requirements for such technical validation as well as the means to achieve this in a resource efficient manner.

6.5.4.3 Reporting Level

In a third step the reporting levels for each organisation were analysed. Three aspects were considered: the reporting scope (the collection of only high-severity occurrences vs. any situation that may or may not affect safety), the underlying definitions and the consistency of the reporting system over time.

The three chosen criteria are not an exhaustive list of the factors affecting the reporting level. Indeed, reporting levels can be influenced by various moderating and confounding effects (e.g. safety and reporting culture). The three aspects of reporting scope, underlying definitions, and their consistency were chosen because they are factual. Any organisation should have clear guidelines about which safety data to collect and its underlying definitions. Consistency was addressed in a stakeholder survey and the details were covered in section 6.5.4.2.

Methodology

First, the reporting scope of the twelve databases was evaluated. Subsequently, the definitions underlying the twelve reporting systems were compared to the definitions used in this thesis (refer to Chapter 4 section 4.5). The method of data collection was described in section 6.5.4.2. Table 28 summarises the reporting scope and comparability of definitions in the twelve reporting systems. The consistency of the reporting systems over time is discussed subsequently.

Table 28: Reporting level

Database	Reporting scope										Underlying definition's conformity to this research' scope													
	Excursions		Collisions / Incursions			FOD		Wildlife			Excursions			Collisions			Incursion			FOD			Wildlife strikes		
	Only high-severity events	All occurrences	Collisions	IN - only high-severity events	IN - all occurrences	Only high-severity events	All occurrences	All wildlife	Only bird strikes	Zoning	Conform	Non-conform	Def. not exist.	Conform	Non-conform	Def. not exist.	Conform	Non-conform	Def. not exist.	Conform	Non-conform	Def. not exist.	Conform	Non-conform	Def. not exist.
UK CAA MORS		✔	-		✔		✔	✔		Unknown		✔				✔		✔				✔			✔
CAA NZ ASMS		✔	✔		✔	✔		-	-	Unknown			✔			✔			✔			✔	-	-	-
CAA Norway ECCAIRS		✔	✔		✔		✔	✔		Unknown		✔			✔			✔				✔			✔
FAA RI database[a]	-	-	-		✔	-	-	-	-	-	-	-	-	-	-	-	✔			-	-	-	-	-	-
FAA AIDS		✔	-	-	-		✔	-	-	-		✔		-	-	-	-	-	-			✔	-	-	-
Signature Flight Support SHEBBA		✔	✔		✔		✔	✔		Unknown			✔			✔			✔			✔			✔
Avinor ATC MESYS		✔	✔		✔		✔	✔		Unknown		✔			✔			✔				✔		✔	
Avinor Airports MESYS		✔	✔		✔		✔	✔		Unknown		✔			✔			✔				✔		✔	
Oslo Lufthavn IFS		✔	✔		✔		✔	✔		Unknown			✔			✔			✔			✔			✔
Norwegian A/S AQD[b]		✔	✔		✔		-	-	✔	Unknown			✔			✔			✔	-	-	-			✔
Widerøe Sentinel[c]	-	-	-		✔	-	-	-	-	-	-	-	-	-	-	-	✔			-	-	-	-	-	-
easyJet AQD		✔	-		✔		✔		✔	A			✔			✔			✔		✔				✔

[a] The available database captures only incursion occurrences.
[b] The available database captures only excursions, collisions, incursions, and bird strikes.
[c] The available database captures only collisions and incursions.

Sources: Avinor AS, 2011b, c; easyJet plc, 2009; Federal Aviation Administration, 2010c, 2011b, d, 2012a; Luftfartstilsynet, Accident Investigation Board Norway, 2010; National Transportation Safety Board, 2011; New Zealand Civil Aviation Authority, 2011; Norwegian, 2011; Oslo Lufthavn AS, 2011a; Structured communication with easyJet plc Safety Analysts and Investigatiors, July 2011; Structured communication with FAA Runway Safety Office Analysts, August 2011; Structured communication with Flight Safety Manager Norwegian, June 2011; Structured communication with Health Safety Environment Manager Signature, June 2012; Structured communication with Oslo Lufthavn AS Risk Manager, June 2011; Structured communication with Safety Analyst Avinor AS Airports, January 2012; Structured communication with Safety Analyst UK CAA, January 2012; Structured communication with Safety Department CAA NZ, December 2011; Structured communication with Safety Department Wideroe, June 2012; Structured communication with Safety Investigatiors Avinor AS ANSP, June 2011; Structured communication with Senior Advisor Analysis CAA-Norway, December 2011; The European Parliament and the Council of the European Union, 2003; UK Civil Aviation Authority Safety Regulation Group, 2002, 2011

Results

The analysis of the reporting scope identified that the FAA AIDS database underreports issues relevant to airport surface safety. There is currently no regulatory requirement to report excursion and FOD incidents in the U.S. (Structured communication with FAA Runway Safety Office Analysts, August 2011). The AIDS database claims to contain accidents and incidents (Federal Aviation Administration, 2013a); however, with, for example, only 35 relevant FOD occurrences reported from 1979 to 2009 this data appears underreported. Hence, the FAA excursions and FOD data should only be used with

the notation of underreporting. In addition, the U.S. government has raised concerns about the accuracy of the FAA's Runway Incursion database. It is expected that an additional 300 to 600 incidents daily in which planes get too close to each other would be revealed if automatic tracking software were used (Halsey, 2013). This in turn justifies the need for a technical validation of the descriptive narratives of occurrences.

In order to make the reported number of surface safety occurrences comparable across countries and organisations, the level of underreporting would need to be estimated. In order to do this, the ratio between accidents and incidents would have to be determined. Although reliable numbers on the frequency of accidents can be gathered from the national Accident Investigation Boards, the estimation of a ratio between accidents and incidents in ATM operations is difficult, and a method for doing this has not yet been proposed.

General studies in systems with robust safety defences, such as aviation, however, indicate that for every accident dozens of incidents occur (Phimister*, et al.*, 2004) but, in aviation, a ratio could only be proposed based on a holistic data set that combines the viewpoints of all relevant stakeholders. In order to aggregate data sets, however, the underlying quality needs to be taken into account, which results in a 'chicken and egg problem'. Even if one could aggregate the data of a country in which every stakeholder seems to collect every occurrence, such as Norway, the transferability of this to another system (e.g. country) is questionable.

Subsequently, the definitions in terms of surface safety used by the considered organisations were analysed. Among the twelve organisations, four do not have any formal definitions in place for accident and incident types. Another six organisations only had definitions for specific occurrence types. Only the FAA Runway Incursion Database and Wideroe's database had definitions for the occurrence types captured in their database. The FAA's reporting system, however, is specifically designed for incursions and does not capture any other occurrence type. Likewise, only data for incursions was available from Wideroe for this research. Hence, current reporting systems do not allow for comparison of their underlying definitions and, therefore, it cannot be determined whether all databases collect the same data. That the data is comparable in relation to its underlying definitions has to be a major assumption when aggregating such data, and leads again to the conclusion that the fundamentals upon which the industry and Safety Management Systems are based are rather weak: the safety data which is currently being used for safety mitigation strategies cannot be clearly defined.

Concerning the consistency of reporting systems the data was evaluated overall as being consistent. The safety data providers stated that there have been no major changes in the reporting systems over the period the data considered in this research has been collected. Some organisations employed different or no data systems in the past (e.g. easyJet, Norwegian). However, if available, such data was not considered in the current study. In addition, some safety data providers (e.g. easyJet) are changing their reporting system due to the perceived limitations of their current system. The CAA – Norway acknowledged that the introduction of electronic reporting along with more comprehensive report obligations coming from the EU directive led to an increase in reports in 2011. The CAA Norway's data considered in this research, however, covers the years 2008 to 2010 and is not affected by this change.

Regarding the definitions, a major change influenced the industry. Most states have adopted the ICAO's definition of runway incursions[7] over the last five years. This change of definitions has influenced the number of reports in some countries (e.g. U.S. Federal Aviation Administration, 2008b). The current research considers incursions in general, i.e. any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the manoeuvring area and hence this change does not influence the number of reports. The FAA AIDS database, meanwhile, dates back to 1978 (Federal Aviation Administration, 2013a) and it is not known whether the reporting system and or definitions may have changed over this period of time.

6.5.4.4 Discussion

To summarise, the first part of the data quality assessment evaluated all databases to be internally valid. In fact, no differences were identified between the data sets in terms of internal quality. However, it was evident that there was a need for external data quality assessment. Consequently, a data quality index reflecting differences in the quality of reporting systems in comparison to an ideal reporting system was developed. This DQI gives an indication as to the extent to which a database is able to capture the causal factors underlying airport surface safety occurrences. Part three analysed each organisation for its reporting levels. It was identified that, overall, the fundamentals of SMS are weak and that

[7] Runway incursion: "Any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft" (International Civil Aviation Organization, 2007)

safety data cannot be clearly defined. In addition, an indication of the level of underreporting of certain databases was given. The following paragraphs use these findings to conclude whether the databases can be aggregated.

Three types of data analysis are possible using airport surface safety data: i) an analysis of occurrence rates, ii) an analysis of causal factors for taxonomic purposes, and iii) an analysis of causal factors in order to develop a statistical model. These are considered in turn.

i) Based on the analysis of reporting levels it can be concluded that occurrence rates should not be compared among organisations due to the level of underreporting and the unclear scope of data collection. Only accidents and runway incursions can be compared, as the ICAO sets clear definitions for these occurrences and they are routinely reported (International Civil Aviation Organization, 2001c, 2005d). It may be possible to analyse trends, as shown in Figure 58.

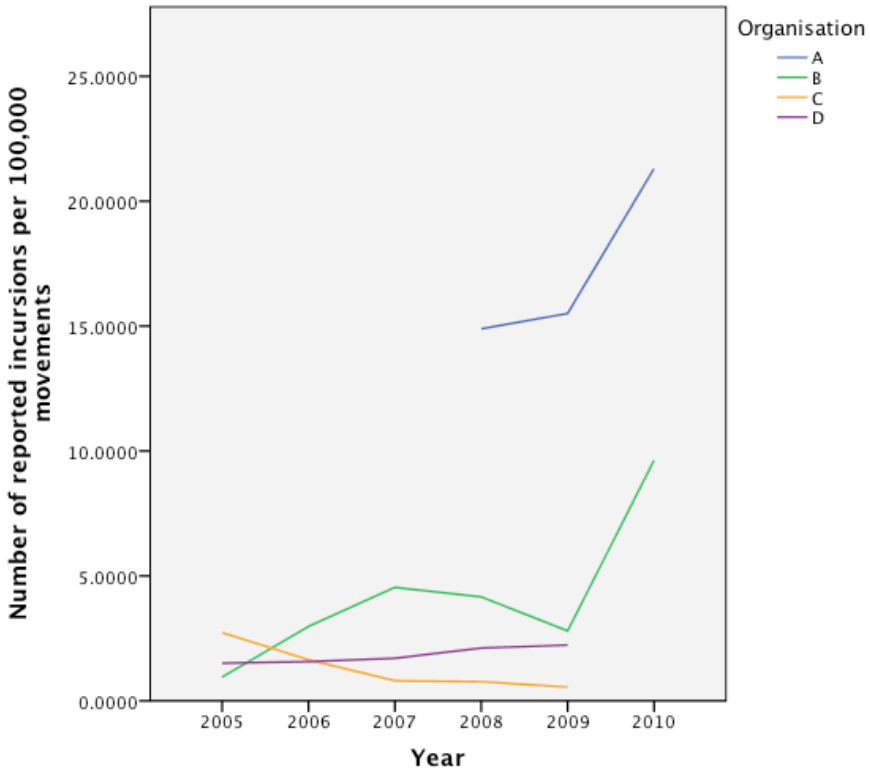


Figure 58: Number of reported incursions per 100,000 movements

Figure 58 shows the normalised number of reported incursions for four of the data sets. Whilst the number of occurrences remained fairly stable in one of the databases, it increased significantly for two organisations, and decreased slightly for another one. However, comparing these trends is misleading as there are good reasons why fluctuations might exist among the countries. In the case of organisation A, the increase in occurrences is largely due to the organisation's efforts to promote a just culture and improve its reporting culture through training and awareness campaigns for their staff. Furthermore, a younger generation of safety-educated individuals is now employed in management positions. This has led to a change in the mind-set and safety culture in the organisation, leading to an increase in reporting. Therefore, occurrence rates cannot easily be compared between organisations.

ii) Data quality really comes into its own when analysing causal factors. In terms of airport surface safety, it was highlighted that the currently practiced piecemeal approach is insufficient and that a holistic approach requires the aggregation of databases reflecting the different stakeholder viewpoints. Section 6.5.4.2 proved that different databases capture the causal factors to a different level of detail. Thus, data reflecting different stakeholder perspectives needs to be aggregated for taxonomic purposes, i.e. to get a full understanding as to why airport surface accidents / incidents occur. A detailed cross-stakeholder comparison is shown in the next two chapters. Any analysis, however, should be interpreted in light of the developed DQI. For instance, when interpreting the causal factors extracted from one database in isolation, the DQI provides a robust indication of the extent to which the causal factors are captured.

iii) Finally, causal factors data can be used to develop statistical models that quantify the relationship between occurrences and their underlying causal factors. It has been concluded, above, that occurrence rates should not be compared between organisations due to the level of underreporting and the unclear scope of data collection. The difference in reporting levels also influences the modelling of causal factors. If the causal factors were aggregated, any statistical model would be biased by the different reporting levels in favour of the stakeholder with the better reporting culture. Thus, causal factors data should not be aggregated for modelling purposes.

Figure 59 summarises the data quality assessment framework and its major findings.

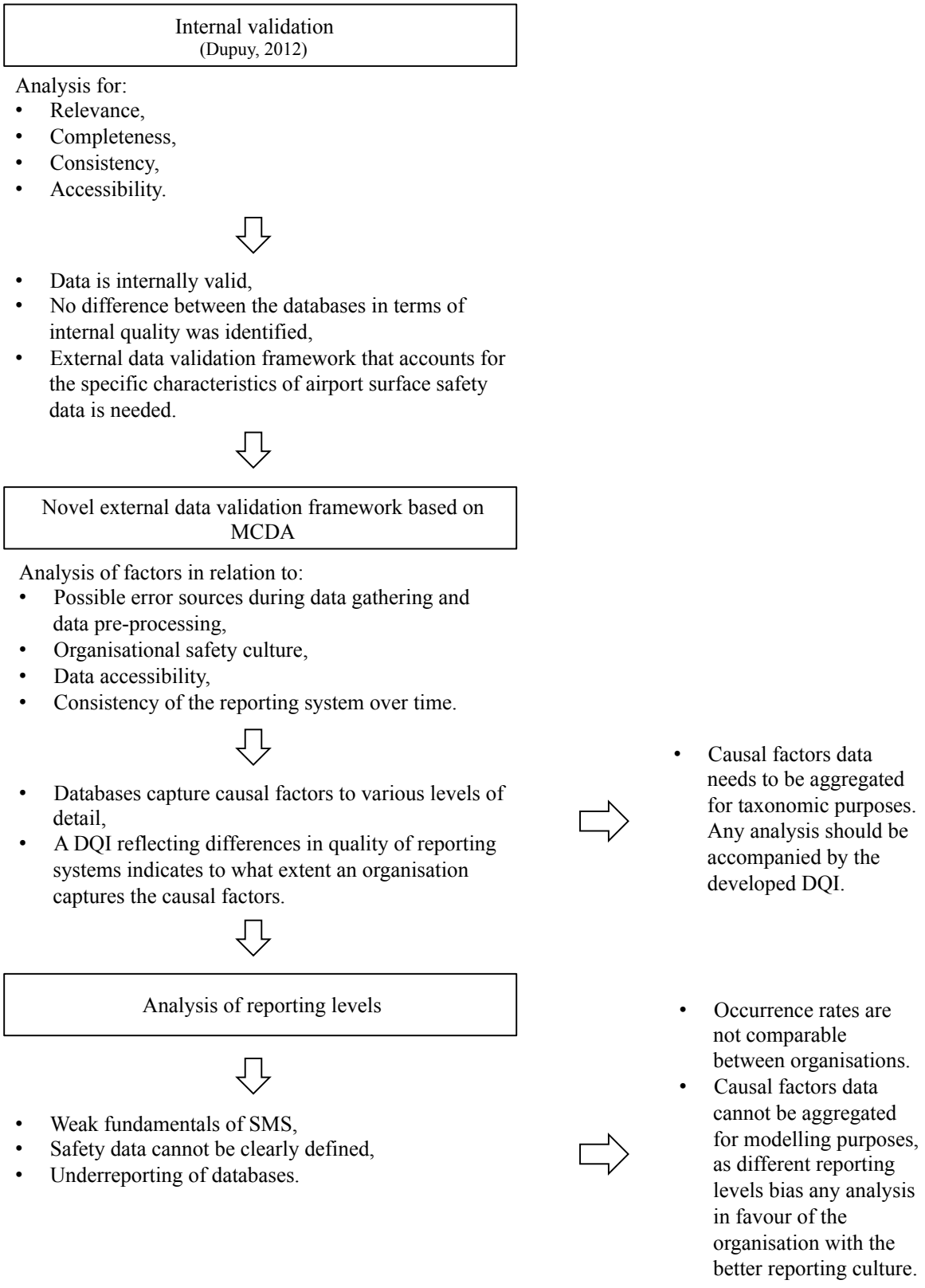


Figure 59: Summary data quality assessment framework

6.5.5 Conclusions Data Quality Assessment

The nature of airport surface safety is such that there is a need to account for data from a number of stakeholders. These stakeholders may possess databases differing in quality, and aggregate this data for subsequent analysis so as to provide robust safety assessment and risk mitigation. To address the data quality problem arising from the aggregation of multi-organisational databases, this thesis has developed a framework for a holistic data quality assessment. To account for the specific characteristics of airport surface safety data a novel external data validation framework has been developed. Quantitative weights were derived for twelve safety databases. The developed DQI indicated that databases with a higher DQI are able to capture the causal factors underlying airport surface occurrences in greater detail. Hence, it is worth investing in good quality safety data and its collection. These weights combined with an internal data quality assessment and an indication of the reporting level of an organisation can give a robust indication of the quality of a database.

The analysis also highlighted the deficiencies of current reporting systems in such fundamental aspects as the definition of occurrences. Sustainable risk management needs to be stronger in a number of fundamental areas. Organisations need to introduce formal definitions for the data they collect in order to guide the data collection process, both for their own sake and also for inter-organisational comparisons. To achieve the required future cooperation of aviation stakeholders such definitions should be standardised. The CAST/ICAO Common Taxonomy Team, for instance, attempts to create a standardised industry language (Commercial Aviation Safety Team / International Civil Aviation Organization Common Taxonomy Team, 2008b). In terms of airport surface safety, however, the given definitions seem insufficient and, in any case, are not applied in any of the analysed organisations. Overall, such common taxonomies are a move in the right direction, but need improvement and promotion. Also, policies at the global and national level need to address these limitations and provide robust guidelines for SMS and data collection systems.

There are on-going attempts to collect and compare safety data at a multi-national level. The European Coordination Centre for Aviation Incident Reporting System (ECCAIRS) collects and analyses safety data from EU States with the objective to improve transport safety. As shown in this research, however, such systems combine and compare data of different quality. Even if reporting states collect data to a ‘common standard’ the data will still vary in quality due to various moderating and confounding factors. The lack

of common taxonomies and reporting systems is a barrier for the required incorporation of the stakeholders. The fundamentals of the industry have to be clearly defined and a common industry language needs to be applied, since otherwise there is a danger that incomparable data is aggregated. This in turn would lead to inaccuracies in risk assessments and the mitigation strategies that are based upon them.

The conclusion that safety data is currently not comparable across organisations also raises the question whether other aviation data is comparable. For example, new technologies such as A-SMGCS are currently being developed and introduced at major European airports (e.g. London Heathrow, Frankfurt Airport, Zurich Airport) and it is questionable whether all airports have a common understanding about what it is, what it includes, and how its performance is measured. Future research, therefore, should address the comparability of aviation KPIs.

Overall, on-going promotion of safety is required to improve reporting levels. This includes operational staff 'on the ground', management and regulators. Stakeholders need to go beyond their current thinking by analysing the bigger picture and collecting occurrence data that reflects the safety of the whole system rather than their particular area of responsibility. Only through such a change in the mind-set within organisations will it be possible to collect comprehensive and comparable datasets to conduct robust safety analysis and develop effective risk mitigation methods.

The external data validation framework developed in this research (in section 6.5.4.2) is recommended for use by both practitioners and researchers in data quality assessment in aviation safety. The basics of the framework are such that it is transferrable to safety databases in other modes of transport, with several operators e.g. railways. Furthermore, the technique is sufficiently flexible for further development to provide quality measures at different levels, e.g. through technical validation greater granularity in the validation can be provided.

6.6 Database Introduction and Data Pre-Processing

This section presents the twelve databases in more detail. Where applicable, the necessary data pre-processing and its output are described also.

6.6.1 FAA RI Database

The data provided by the FAA Runway Safety Office contained 5,274 occurrences for the period 2005 to 2009. The available data fields are:

- Event date;
- Incident type (possible categories: Vehicle / Pedestrian Deviation (V/PD), Pilot Deviation (PD), Operational Deviation (OD));
- Runway Incursion (RI) (possible categories: yes, no);
- Category Rank, i.e. the severity (this information is only given for runway incursions (RI));
- Airport and IATA airport reference code;
- Aircraft types involved;
- Descriptive narrative;
- Visual Meteorological Conditions (VMC)[8] (possible categories: yes, no);
- Day (possible categories: yes, no).

Due to the large amount of data available, a sample of four representative regions was chosen, consistent with the data requirement of diversity. The FAA assisted in the selection of the sample by recommending regions that meet the data requirements in Table 22 (Structured communication with FAA Regional Runway Safety Manager, September 2011). The following regions were chosen:

- Northeast (NE): New England Region[9] and Mid-Atlantic[10]: 572 occurrences
- Southwest (SW)[11]: 559 occurrences
- Northwest Mountain Region (NMR)[12]: 490 occurrences
- Western-Pacific (WP)[13]: 1254 occurrences.

The FAA also provided a database containing normalisation data, i.e. number of movements per airport per year (Federal Aviation Administration, 2010g).

[8] Meteorological conditions expressed in terms of visibility, distance from cloud, and ceiling, equal or better than specified minima (International Civil Aviation Orgnanization, 2005b)
[9] Connecticut (CT), Maine (ME), Massachusetts (MA), New Hampshire (NH), Rhode Island (RI), Vermont (VT)
[10] New Jersey (NJ), New York (NY), Pennsylvania (PA)
[11] Arkansas (AR), Louisiana (LA), Texas (TX), New Mexico (NM), Oklahoma (OK)
[12] Colorado (CO), Idaho (ID), Montana (MT), Oregon (OR), Utah (UT), Washington (WA), Wyoming (WY)
[13] California (CA), Nevada (NV), Arizona (AZ), Hawaii (HI)
([9-13] Federal Aviation Administration, 2000)

6.6.2 FAA AIDS

The FAA AIDS database contains incident data for all occurrence categories of civil aviation. The data is for the period from 1978 to date (Federal Aviation Administration, 2013a). In order to extract the relevant data for excursions and FOD occurrences a keyword search for the following terms was conducted:

- Excursion
- Overshoot
- Overrun
- Undershoot
- Underrun
- Veer(-)off
- FOD
- Foreign Object(s)
- Foreign Object Damage
- Foreign Object Debris

The data extraction was validated with two Safety Analysts from the FAA's Runway Safety Office, whereby the SMEs were asked to systematically assess the list of keywords and to comment on their completeness. 396 excursions were found for the whole U.S. spanning a time period from 1978 to 2009. For FOD, 35 occurrences were identified. These numbers refer to relevant excursions and FOD occurrences only, i.e. accidents / incidents that comply with the definitions of airport surface safety introduced in Chapter 4. For example, the key term search identified approach incidents listed as excursions, or FOD occurrences outside the manoeuvring area. Such data was excluded from the analysis.

The database provides for each occurrence location information, operator information, narrative findings[14], weather / environmental information, and pilot information.

6.6.3 Signature SHEBBA

Signature's database contained 10,198 occurrences for the period from 2007 to April 2012. The ground handling data contained mainly accidents / incidents that occurred on the apron (e.g. personal injuries during handling, damaged equipment), which is outside the scope of this research. To identify the relevant occurrences a keyword search was conducted for the first 1,000 occurrences. This was checked by reading all 1,000 reports to

[14] Full narratives are provided on all incident reports with an active event date of January 1, 1995 or greater (Federal Aviation Administration, 2012a)

check whether the keyword filter identified all relevant incidents. This led to the refinement of the keywords resulting in the following terms:

- Runway / RWY
- Taxi(-)way / TWY
- Taxilane
- Incursion
- Collision
- Near miss
- Movement area
- Manoeuvring area
- Airfield
- Double(-)white line
- Double(-)yellow line
- Hold line
- Towing
- Infringement
- Excursion
- Overshoot
- Overrun
- Undershoot
- Underrun
- Veer(-)off
- FOD
- Foreign Object(s)
- Foreign Object Damage
- Foreign Object Debris
- Different animals (including e.g. birds, deer, rabbit)

The rest of the data was filtered using the keywords. 103 relevant incidents were identified (32 U.S., 71 UK). Signature's database contains the date of occurrence, the airport and a description of the incident.

Normalisation data, i.e. number of ground handling operations per airport per year, was not available.

6.6.4 UK CAA MORS

A data request was sent to the UK CAA to provide excursion, incursion, FOD, and wildlife strike data that occurred on both runways and taxiways. In contrast to Signature's SHEBBA database, the UK CAA's data, for example, contains only the requested occurrence types and not all accidents and incidents that occurred in the UK air traffic system. Two years of data (2009-2010) were available. Two transformations were necessary. Data screening revealed that the data contained all FOD occurrences reported at airports. The FOD data was analysed and the occurrences that happened on runways / taxiways were extracted. FOD occurrences on the apron were excluded. In addition, the data contained reports of accidents / incidents outside the UK. The data was filtered

according to locations and only UK-based occurrences considered. In addition, double entries were removed from the database. After data pre-processing, the database contained 1,038 entries (279 excursions, 539 incursions, 66 FOD, 154 wildlife strikes). The database provides information on:

- Date and time of occurrence;
- Descriptive narrative;
- Event descriptions (i.e. causal factors);
- Flight details (e.g. aircraft type, weight group).

The number of movements per airport per year were used to normalise the data. These airport statistics are publically available from the UK CAA (UK Civil Aviation Authority, 2011d).

6.6.5 easyJet AQD

Data was requested from easyJet for incursions, excursions, FOD and wildlife strikes that occurred on both runways and taxiways. It was problematic to extract the data in a suitable format from the AQD data system. Therefore, incursion, excursion and FOD data was provided in a combination of Microsoft® Excel® and Word® format. A total of 168 accident / incident reports were provided. The data in Excel® format contained the date and location (i.e. airport) of the occurrence, an incident classification (i.e. incident type), an internal severity factor and risk code, the aircraft model and call sign, and a descriptive narrative of the occurrence.

When extracting the data from AQD it was not possible to extract all available information to Excel®, as the system automatically cut-off every cell after 250 characters. The full occurrence report could only be extracted to a Word® format. The Word® report also contained operational details (e.g. duty day, sector, pilot age), event descriptors (i.e. causal factors), and investigation findings where available. Data pre-processing was needed to combine both files (Excel® and Word®). In addition, a high-level analysis, whereby the descriptive narratives of the occurrence reports were read, identified a small number of occurrences labelled as incursions which actually happened on the apron. These occurrences were excluded from any further analysis. The final database after data pre-

processing contained all available details for 145 relevant occurrences (69 incursion, 1 excursion, 75 FOD) that occurred between 2005 and 2010.

Wildlife strike data was provided separately in a text file, which contained next to wildlife strikes other incidents that happened during the landing and take-off phases of flight. This file contained over 6,000 additional occurrences. An analysis of the descriptive narratives of 100 randomly selected wildlife strike reports revealed that this data did not contain any details as to why wildlife strikes occurred. Due to the limited amount of information to be extracted from these occurrences, this data was not considered for further analysis.

easyJet also provided an internal database with the number of the airline's operations per airport per year (easyJet plc, 2010d).

6.6.6 CAA Norway ECCAIRS

Data for all relevant surface safety occurrence types was requested from the CAA Norway. Each occurrence type was supplied in a separate Excel® file:

- Runway incursions (460 oc.)
- Taxiway incursions (143 oc.)
- Ground collisions (36 oc.)
- Runway excursions (140 oc.)
- FOD (173 oc.)
- Wildlife strikes (120 oc.)
- Bird strikes (1715 oc.)

In addition, data in relation to aerodrome markings (186 occurrences), and runway conditions (137 occurrences) was provided. The data captured occurrences from 2008 to 2010 and provided information on:

- Date, time, and location (i.e. airport) of the occurrence, phase of flight;
- Occurrence category (i.e. incident type);
- One descriptive factor (i.e. causal factor on the highest level) and the injury level;
- Occurrence summary written by the CAA Norway;
- Original reports from pilots, ATC and the airport.

The data required three forms of data cleaning:

1) The data contained multiple double entries of incidents. In some cases different stakeholder reports (i.e. pilot, ATC, airport) were represented in multiple rows. In

this case the statements were combined in one row so that one accident / incident is represented in one row. Others were simply duplicates and had to be removed.

2) Occurrences that did not fall into the scope of this research were removed (e.g. FOD on the apron).
3) Occurrences at non-Norwegian airports were excluded.

In addition, a high-level analysis of the bird strike data revealed that these reports did not contain causal factors. Due to the limited amount of information to be extracted from these occurrences, this data was not considered for further analysis. Finally, a master file was created containing a total of 600 relevant occurrences (6 collisions, 332 incursions, 29 excursions, 125 FOD, 108 wildlife strikes).

6.6.7 Avinor ANSP MESYS

Avinor ANSP provided their complete database of aviation accidents / incidents from 2008 to 2010, a total of 4,799 occurrences. A substantial amount of data pre-processing was required. Firstly, the database had to be translated into English, since Avinor keeps its data in Norwegian. Secondly, the relevant occurrences had to be extracted. In order to do so the column 'occurrence type' was used. Overall, 105 occurrence categories were identified in the database and translated into English using Google Translate. Data that was clearly relevant to this project was extracted, such as:

i. Entry of the runway without clearance;
ii. Unauthorised traffic on the manoeuvring area;
iii. Aircraft, vehicles, people or animals moving on the manoeuvring area without clearance;
iv. Aircraft, vehicles, people or animals moving on runway without clearance;
v. Aircraft, vehicles, people or animals moving on taxiway area without clearance.

The analysis of the occurrence categories showed that occurrences could be classified in several ways. For example, an incursion on a runway could be classified as i, ii, iii, and iv. Thus, this thesis could not rely on the given classification to identify the relevant occurrences. A simple keyword search, as done for the SHEBBA database, also proved difficult, since the database was kept in Norwegian. To extract the relevant accidents and incidents, all occurrence categories that could contain relevant accidents / incidents were extracted, including categories such as:

i. Failure to comply with the relevant procedures;
ii. Aircraft does not comply with the relevant ATM procedures;
iii. Violations of traffic regulations.

A total of 46 categories were considered as potentially relevant. These occurrences were translated using Google Translate followed by reading all of them to identify the relevant ones. Using Google Translate brings the risk of mistranslations and can influence the data's accuracy. Therefore, databases that require translations have been down-weighted in the data quality assessment. In case a translation did not make sense, a native speaker was asked for clarification. The final database contained 552 surface safety occurrences (2008-2010) to be considered in this research (361 incursions, 18 excursions, 10 FOD, 163 wildlife strikes).

Avinor ANSP's database is the most comprehensive of those studied here, showing amongst other things:

- Occurrence details (e.g. date, time, IATA code, airport, location of occurrence on the airport);
- Details of aircrafts involved (e.g. call sign, registration, aircraft model, flight phase);
- Weather information (e.g. weather report, light conditions);
- Runway details (e.g. breaking action, contamination);
- ATC details (e.g. sector, traffic density, workload, airspace details);
- Descriptive narrative of the occurrence;
- Investigation report.

6.6.8 Avinor Airports MESYS

Avinor's Airports division also uses the MESYS system. A special feature is that Avinor Airports keeps two separate databases, one for the three medium-sized airports, i.e. Bergen, Stavanger, Trondheim (458 occurrences), and one for all other airports in the country, except OSL (706 occurrences). To capture all safety occurrences from the airport's perspective both databases should be combined. Since these two databases are also based on MESYS, they contain the same data fields as the ANSP database described in the previous section. Avinor Airports provided both databases. Again, the databases contained all aviation accidents / incidents from 2008-2010 and were kept in Norwegian.

To begin with, both databases were combined. Subsequently, the relevant occurrences were extracted following the same methodology as described for the Avinor ANSP database (section 6.6.7). This time the database contained 56 different occurrence classifications, out of which 28 were considered as possibly relevant and thus further analysed. The final database after pre-processing contained 759 relevant occurrences (7 collisions, 69 incursions, 9 excursions, 163 FOD, 511 wildlife strikes).

The number of movements per airport per year is publically available from Avinor's homepage and has been used to normalise the number of occurrences from the CAA Norway and Avinor (Avinor AS, 2011d).

6.6.9 OSL IFS

OSL is a subsidiary company of Avinor. Its database is similar to Avinor's but contains less data fields. OSL also provided a full safety database capturing all aviation occurrences from 2008-2010. The database is kept in Norwegian and contained 4,621 accidents / incidents. To extract the relevant occurrences the data was filtered using the same methodology as described for the MESYS system. The data was filtered for possibly relevant occurrences using OSL's occurrence classification. The database contained 98 different occurrence classifications out of which 20 were evaluated as possibly relevant. These were extracted, translated using Google Translate, and analysed. After this pre-processing, the database contained 223 relevant occurrences (4 collisions, 155 incursions, 4 excursions, 41 FOD, 19 wildlife strikes). The IFS database provides information on:

- Occurrence details (e.g. date, time, location of the occurrence at the airport);
- Internal severity assessment and priority to handle the occurrence;
- Descriptive narrative, investigation findings and comments on the occurrence.

Movement data to normalise the number of incidents (i.e. per airport per year) was taken from Avinor as described in the previous section (Avinor AS, 2011d).

6.6.10 Norwegian AQD

The data from Norwegian was supplied in two formats, Microsoft® Excel® and Word®. Separate files were provided for the following occurrence types in relation to landing, take-off and ground operations:

- Aborted take-offs (97 oc.)
- Airspace / ATC incidents (378 oc.)
- Approach incidents (199 oc.)
- Birds (270 oc.)
- Communications (45 oc.)
- Excursions (2 oc.)
- Incursions (7 oc.)
- Landing incidents (47 oc.)
- Missed approaches (179 oc.)
- Weather-related incidents (124 oc.)

The data was for the period from 2007 to October 2011. Some occurrence types are directly relevant to this research (e.g. incursions). Others (e.g. landing incidents) appear not directly related, however, may still contain relevant accidents / incidents. Hence, all occurrences were read and the relevant ones extracted. For this, the Excel® file was used. Similar to easyJet, the Norwegian's AQD database also cut-off every cell after 250 characters. In case information was missing, the Word® files were used. For relevant occurrences, all information was transferred into the Excel® files. As Norwegian's pilots report in English translation was unnecessary. Relevant occurrences were found in the data files for aborted take-off, airspace / ATC incident, communications, excursions, incursions and landing incidents. Finally, a master file was created combining all relevant occurrences (310 occurrences: 39 incursions, 2 excursions, 269 wildlife strikes). The database contains:

- Date, time, location (airport) of occurrence;
- Occurrence title, descriptive narrative and investigation findings, if available; and
- Aircraft type and registration.

Movement data to normalise the number of incidents (per airport per year) could not be obtained from Norwegian. The organisation regarded this data as confidential.

6.6.11 Wideroe Sentinel

Wideroe provided only data for 27 incursions / collisions (2007- June 2012). In addition, the company stated that they have had no excursion reported since 2007. FOD

and wildlife strike data is not available for this research. As the data is kept in Norwegian, Google Translate was used. The database contains the date and airport of occurrence, the incident title and descriptive narrative, as well as safety actions to be taken.

Normalisation (i.e. movement) data is not available for Wideroe.

6.6.12 CAA NZ ASMS

NZ CAA's database contains all accidents / incidents that occurred in the flight phases: parking, taxiing, take-off, and landing from 2000 to 2009. The database contains two spread-sheets. The first contains accidents / incidents with findings (2,204 occurrences). These are occurrences that have been investigated and the causal factors identified. The second spread-sheet contains 16,257 occurrences without causal factors (e.g. bird strikes). Both spread-sheets together comprise the full database.

Due to resource and time constraints, the analysis of the data in this thesis aims only to provide an insight into the practices in New Zealand. Therefore, it was decided to consider only the occurrences with findings, since these are the ones that could potentially provide the best overview of causal factors. This spread-sheet was read and the relevant occurrences that complied with the definitions used in this research were extracted. The final database contained 220 occurrences (9 collisions, 148 incursions, 62 excursions, 1 FOD) and provided information on:

- Date, time, flight phase, and location (i.e. airport) of occurrence;
- Descriptive narrative of the occurrence; and
- Findings and causes.

The NZ CAA also provided an internal database with normalisation data, i.e. number of movements per airport per month (Civil Aviation Authority of New Zealand, 2010b). From this, the number of movements per airport per year was calculated.

6.7 Data Coding and Validation

After the databases have been pre-processed, the occurrences were analysed for their underlying causal factors. Taxonomies can be used to analyse qualitative data, in particular, to code such data. When using taxonomies for data coding, the descriptive narrative is read, the causal factors are identified, and one or more corresponding codes from a chosen taxonomy are assigned. Subsequently, the data is analysed.

Chapter 5 (section 5.2.7) highlighted the lack of integrated taxonomies for the causal factors of airport surface safety occurrences. Therefore, template analysis was chosen as the most appropriate method for the qualitative analysis of the data. The consultation with SMEs (as described in section 6.2.2) revealed that approaches such as grounded theory, whereby a theory is developed straight from data (Glaser and Strauss, 2009), are not advisable for this research since many factors or groups of factors are already known. Template analysis involves the use of an initial template that is refined over time. Such a template can be developed based on the literature, personal experience, case studies, or subject matter interviews, for instance, and the initial template is refined by the incorporation of new material. New codes can be added if a subject is not captured in the template, those that are not used can be deleted, and the ones that have been initially defined on a lower level can be put at a higher level and vice versa (Symon and Cassell, 1998).

The list of causal factors extracted from the literature (Chapter 5 section 5.2.6) was used as the initial template. To refine this template, the descriptive narrative of each occurrence was read and a code assigned. Multiple accident / incident causation theory was assumed, which states that multiple factors combined in a random fashion can cause an occurrence (Hollnagel*, et al.*, 2006). If multiple causal factors were identified, all factors were coded, and, as far as possible, arranged in a chronological order. If the data did not match any existing codes, new codes were added to the initial template. Note that template analysis is an iterative process, and once a new code is added, the previous analysis has to be re-checked for its applicability.

Some databases (e.g. UK CAA MORS) already contained event descriptors, i.e. an analyst had already identified the causal factors. These descriptors were not taken into account during the analysis. To code the data the descriptive narrative was used and, if provided, the investigation findings.

The following example illustrates the process of data analysis. For sensitivity reasons the incident is anonymised.

Example 1:

"Ground Control 1 (GC1) failed to coordinate with Local Control and cleared aircraft (a/c) 1 to cross Runway 27 at Taxiway November (departure end) which conflicted with an a/c 2 on a one half (.50) mile final same runway. Local Control immediately issued a go around to the a/c 2 to avoid loss of separation."

Two pieces of information can be extracted from this incident: i) there was an insufficient coordination between two control units, and in consequence ii) conflicting clearances were issued. The incident does not provide the detail on why GC 1 failed to coordinate. The incident was coded as follows:

- ATC team operations: inadequate coordination,
- ATC: issue of conflicting clearances.

The data coding is based on factual information. That is, only facts that are written in the narratives are taken into account. The following two examples clarify this issue:

Example 2:

"An a/c 1 was taxied to Runway 19 and instructed to hold short, which pilot read back correctly. The a/c 1 taxied across Runway 19 hold lines at approach end without authorisation and conflicted with an a/c 2 on final same runway. The a/c 2 was issued a go around at one (1) mile final. No loss of separation reported."

The incident was coded as follows:

- Pilot: correct read back, followed by an unauthorised manoeuvre,
- Pilot: not stopping at the required position in from of a runway (hold line).

Example 3:

"An a/c 1 crossed the hold short line for Runway 1 at approach end without clearance and conflicted with an a/c 2 on final same runway. The a/c 2 was issued a go around between 1.5 and 2 miles."

The incident was coded as follows:

- Pilot, not stopping at the required position in from of a runway (hold line).

In contrast to Example 2, the report in Example 3 does not mention that the pilot read back. It is unknown whether the pilot did read back or not, and whether this read-back was correct or not. The coding takes only the information that is clearly stated in the report into account, i.e. crossing of the hold line.

In accordance with previous research (Jarvis and Harris, 2008; Nascimento*, et al.*, 2012; Wiegmann and Shappell, 2003) Cohen's Kappa inert-rater reliability test was applied to validate the data coding. Cohen's Kappa computes the extent of agreement between two raters, taking into account the agreement occurring by chance. Three other independent qualified raters were asked to code 300 randomly selected occurrences each. The coding is accepted as reliable if the agreement rate is at least 0.70 (Fleiss*, et al.*, 2003). The reliability checks have been accepted as reliable and the details are discussed in Chapter 9 section 9.2.2, which deals with validity and reliability checks.

6.8 Refined Taxonomy of Causal Factors Underlying Airport Surface Safety Occurrences

The causal factors extracted from the safety data were used to refine the initial taxonomy based on the literature. The refined taxonomy is divided into the five categories of aircraft operations, air traffic control, airport operations, environment, and regulatory system.

Figure 60 shows the first three levels of the refined taxonomy. The second taxonomy level comprises aircraft operations and ATC, split into either technical (e.g. aircraft malfunction) or human-related factors (e.g. pilot-related factors). Airport operations are split into technical (e.g. vehicle malfunction), human (V/PD-related factors), and physical (e.g. airfield layout and infrastructure such as markings, lighting and signage) factors. The environment contains the five sub-categories of weather, geological disturbances, night-time operations, wildlife, and external factors. The regulatory system is split into non-existent, inadequate, and existent but not implemented.

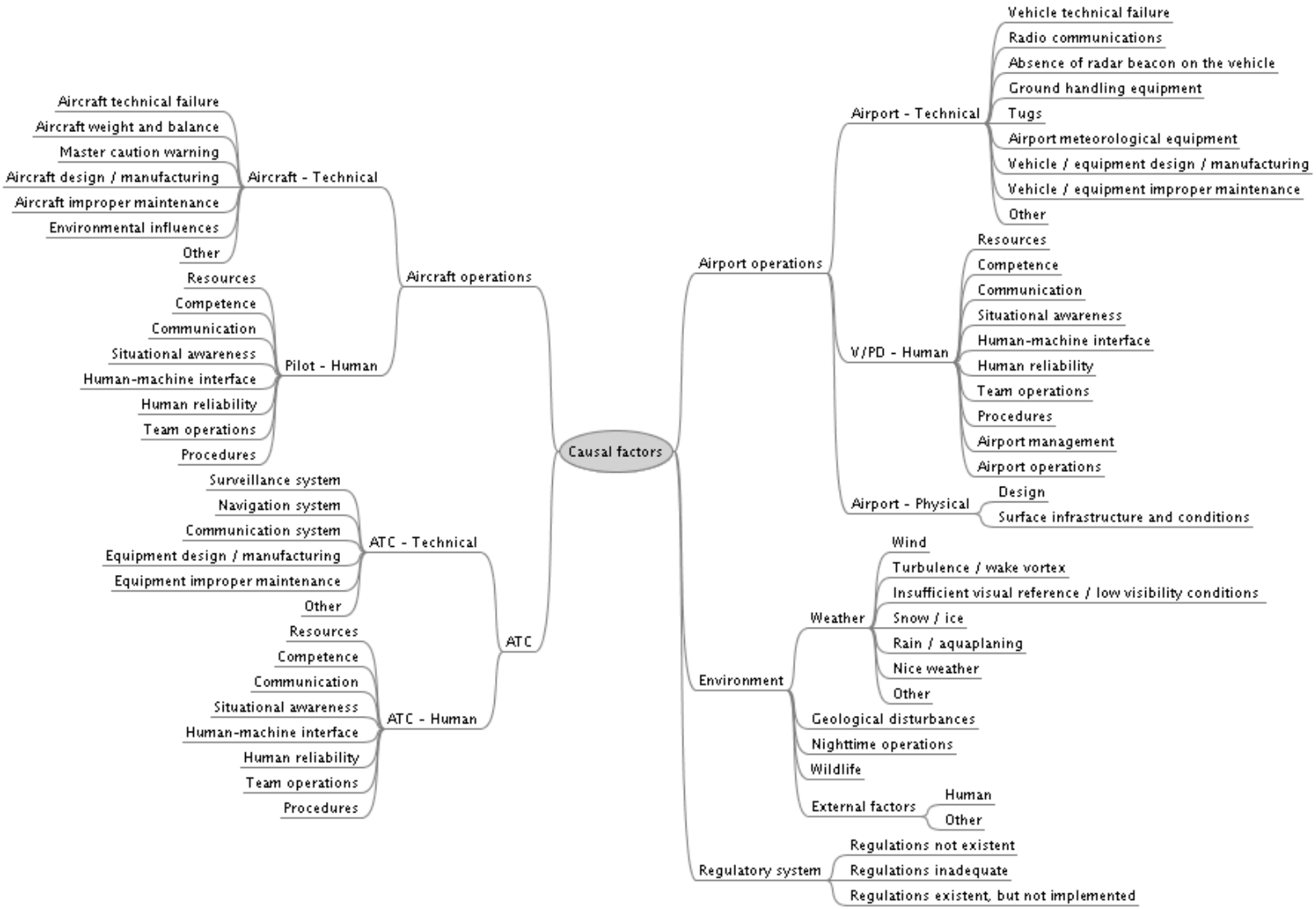


Figure 60: Refined taxonomy after safety data analysis

6.9 Summary

This chapter developed a strategy for the collection of safety data accounting for the limitations of previous research and the specific characteristics of airports. A reference data set combining a total of twelve databases was collected. The databases were introduced and evaluated for their quality. It was found that according to the data requirements defined in Chapter 4, the current safety data are non-compliant in certain aspects (e.g. reporting scope, underlying definitions) and that safety data is currently not comparable across organisations and should therefore not be aggregated (except for taxonomic purposes).

To address the data quality problems arising from the aggregation of multi-organisational databases, a framework for data quality assessment was proposed and applied to the data. In particular, the need to assess the quality of the underlying reporting systems was highlighted and led to the development of a novel external data validation framework. Using the framework, a data quality score was assigned to each database, indicating the extent to which the database captures the causal factors in the context of airport surface safety. The current chapter, therefore, fulfils the fourth research objective and the developed framework is recommended for data quality assessments in aviation safety.

Furthermore, the databases were pre-processed and the methodology for data analysis (i.e. coding) specified. The next two chapters present the findings. The causal factors are presented according to the structure of the refined taxonomy in Figure 60.

7 Analysis of Causal Factors

Chapter 6 presented a reference data set used in this thesis to assess the safety of the airport surface system. The data has been assessed for quality, pre-processed, and analysed to extract the factors that caused the accidents and incidents. This chapter presents the results of the causal factor analysis and compares the factors across stakeholders. With this, the chapter addresses the fifth research objective.

The analysis of causal factors is presented in two parts. Whilst Chapter 7 presents the analysis at the State-level, Chapter 8 explores the differences in the causal factors at the cross-State level.

7.1 Methodology

The twelve databases introduced in Chapter 6 have been analysed to determine the causal factors in five parts. The methodology used for the analysis of the data is detailed below.

1) **Data overview**

To begin with, the datasets are summarised in overview specifying:

- The stakeholder and database,
- The number and type of occurrences that have been analysed,
- The geographical location and number of airports at which the accidents / incidents occurred, and

- The considered time period.

2) Occurrence rates

Subsequently, the data is analysed for trends. Chapter 6 concluded that accident / incident rates should not be compared across organisations and, therefore, occurrence trends are shown for each organisation individually. The data was normalised by the number of movements per airport per year.

3) Frequency analysis

Afterwards, the frequencies of the causal factors are presented, including:

- The number of causal factors extracted from each database,
- The distribution of causal factors on the first three taxonomy levels (that were shown in Chapter 6 section 6.8),
- The top 10 causal factors per database,
- Factor combinations (i.e. the percentage of occurrences to which at least two stakeholders / system components contributed, and the specification of the causal factors involved in these interactions), and
- A wildlife analysis (i.e. specification of animals involved in wildlife strikes and analysis of the causes underlying these occurrences).

4) Comparison of stakeholder viewpoints

In order to identify whether different stakeholders capture accidents / incidents from different viewpoints, the reports of the different databases are subsequently overlapped where possible. To do so, each database was ordered chronologically and the reports were matched based on the date of occurrence and the location (i.e. airport). The analysis includes the following:

- The distribution of reported occurrences per stakeholder (i.e. who reports what),
- The causal factors captured by the different stakeholders in a country, and
- A comparison of multiple reports (i.e. analysis as to whether reports concerning the same accident / incident are complementary).

5) Examination of relationships

Finally, the data is analysed for relationships between occurrence types, causal factors, and stakeholders. Since most variables are categorical, associations (i.e. interactions between the variables) can be analysed by cross tabulation. The Pearson's Chi-Square test of independence is the typical test used to assess whether any association is taking place between two categorical variables and to explain the frequencies expressed in a contingency table. The test compares the actual frequencies observed in certain categories to the frequencies that might be expected in those categories by chance and can be calculated as follows:

$$X^2 = \sum \frac{(n_{ij} - \mu_{ij})^2}{\mu_{ij}} \quad (6)$$

where n_{ij} and μ_{ij} are the observed and expected frequencies, and i and j represent rows and columns in the contingency tables, respectively. In addition, Cramer's V is a measure for the strength of an association between two categorical variables and is used as a post hoc test as shown in equation (7). Cramer's V is computed by taking the square root of the qui-squared statistic (X^2) divided by the sample size (N) and the length of the minimum dimension (k is the smaller of the number of rows or columns) (Agresti, 2007; Field, 2009).

$$\emptyset_c = \sqrt{\frac{X^2}{N(k-1)}} \quad (7)$$

The data was analysed for relationships between:

- Occurrence types and stakeholders,
- Causal factors and stakeholders,
- Occurrence types and causal factors, and
- Causal factors and airports.

Where necessary other methods (e.g. interviews) were used to complement the data analysis, to gain detailed insight into the causal factors, and to enhance the understanding of certain fuzzy areas (e.g. the impact of U.S.-based pilots).

The following sections present the results of the causal factor analysis. This chapter applies the methodology at the State-level and the next chapter at the cross-State level.

7.2 United States

7.2.1 Data Overview

Three databases were analysed for the U.S.: Signature SHEBBA, FAA AIDS, and four regions of the FAA RI database (U.S. Northeast, Southwest, Northwest Mountain Region, Western-Pacific). The data reflects the ground handling, and regulatory / ANSP perspectives, respectively. Table 29 provides an overview of the analysed data.

Table 29: Data overview occurrences U.S.

Stakeholder / database	Geographical location	Number of occurrences					Number of airports involved	Considered time period
		IN	EX	FO(D)	WL	Total		
Regulator / ANSP / RI Database	U.S. NE	572	-	-	-	572	55	2005 - 2009
	U.S. SW	559	-	-	-	559	59	
	U.S. NMR	490	-	-	-	490	48	
	U.S. WP	1254	-	-	-	1254	78	
AIDS	U.S.	-	396	35	-	431	354	1978 - 2009
Ground handling / SHEBBA	U.S.	24	0	7	1	32	15	2007 – April 2012

A total of 2,875 incursions from the RI database spanning over a five-year time period from 2005 to 2009 were analysed. The AIDS database contained a total of 396 excursions and 35 FO(D) occurrences (1978 - 2009). FO(D) occurrences capture both situations where a FO was found on the surface, and occurrences where actual damage was sustained. In addition, 32 surface accidents / incidents were analysed from the SHEBBA database.

7.2.2 Occurrence Rates

Initially, the data was analysed for trends. The incursions captured in the RI database were normalised by the number of movements per airport per year, and Figure 61 shows their trend. The AIDS and SHEBBA occurrences could not be normalised due to missing movement data.

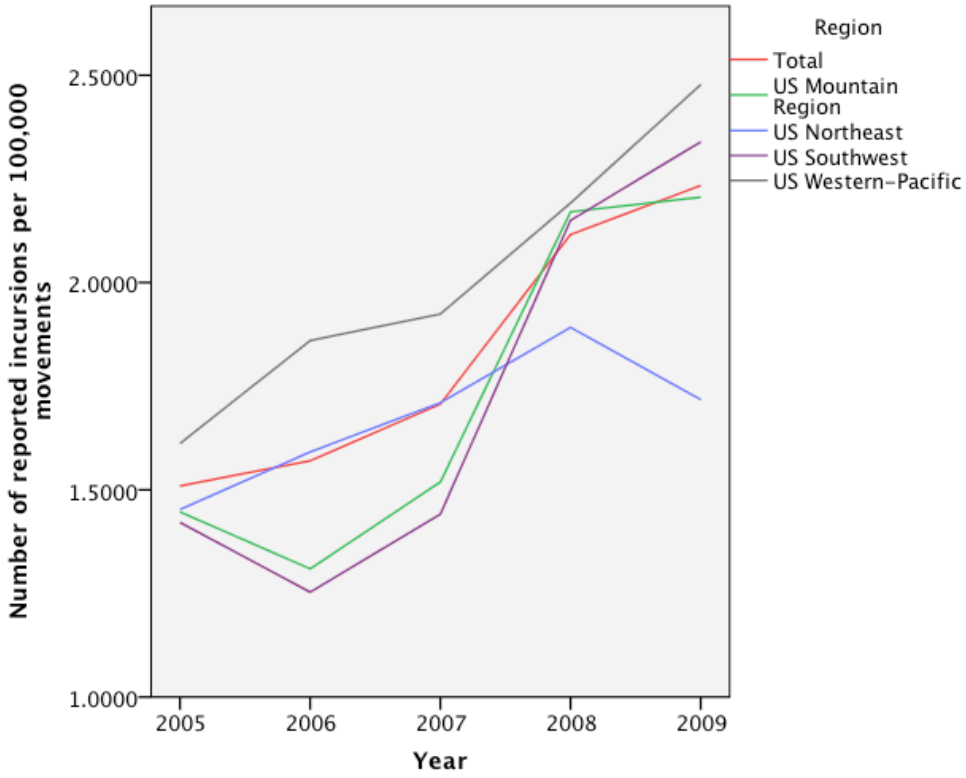


Figure 61: FAA reported number of incursions (per 100,000 movements)

Figure 61 shows that the total number of reported incursions (per 100,000 movements) increased over the time period considered in the four analysed regions. In particular, the rise of occurrences from 2007 to 2008 stands out. This trend is in line with the development of runway incursions in the U.S. (Federal Aviation Administration, 2010d).

The increase in incursions might be linked to the adoption of the global definition of runway incursions by the FAA beginning of the fiscal year (FY) 2008 (Federal Aviation Administration, 2009c). The new definition is broader and classifies more occurrences as runway incursions than had previously been the case, e.g. taxiway incursions are now classified as runway incursions. This thesis considers occurrences on both runways and taxiways. Therefore, the change in the runway incursion definition should have no impact on the overall number of incursions on the manoeuvring area. Indeed, it affects only their severity assessment.

The increase in incursions, therefore, might reflect a change in the safety culture and greater awareness of incursions. In 2007, the FAA together with more than 40 aviation leaders from airlines, airports, ATC, pilot unions and aerospace manufacturers initiated the "Call to Action" in order to reduce the number of incursions. This initiative included an

upgrade of airport markings, airport recurrent training, airport surface analysis of 20 selected airports, pilot training and safety risk analysis of ATC procedures (Federal Aviation Administration, 2008b). In addition, the FAA and the National Air Traffic Controllers Association (NATCA) signed an agreement in March 2008 to create an Air Traffic Safety Action Program (ATSAP), designed to foster a voluntary, cooperative, non-punitive environment for the open reporting of flight safety concerns by ATC (Federal Aviation Administration, 2008a). The increased number of reported incursions, therefore, might only be a reflection of an improved reporting culture.

The occurrence rates were studied further at the airport level and the five airports with the highest occurrence rates were identified for each region. Additional analysis revealed that the majority of these airports handle traffic (i.e. movements) below the national average. This indicates that the less busy airports in terms of traffic movements experience a higher rate of incursions. On the other hand it may be that rather than having more incidents in reality, reporting is better at such airports with much less traffic and more time to report. Appendix V Tables 1 and 2 shows the top five airports for each region, their normalised number of incursions, their total movements (2005-2009) and summary movement statistics for each of the four regions.

7.2.3 Frequency Analysis

This section analyses the causal factors that have been extracted from each of the three databases. The single wildlife strike that had been identified in the SHEBBA database was excluded from the analysis. A total of 5,838 causal factors were extracted from the occurrence reports, and Table 30 shows their distribution across the databases. Again, as shown in Chapter 6, the results of a causal factor analysis should always be interpreted in conjunction with the DQI that has been developed for this research.

Table 30: Data overview causal factors U.S.

Stakeholder	Database	Number of occurrences analysed	Number of causal factors extracted	Number of different causal factors extracted from each database
FAA	RI Database	2875	5235	237
FAA	AIDS	431	550	88
Signature	SHEBBA	31	53	25

Figures 62 and 63 show the distribution of causal factors on the first (Level 1), and second (Level 2) taxonomy level, respectively, and highlight the different causes of the occurrence types.

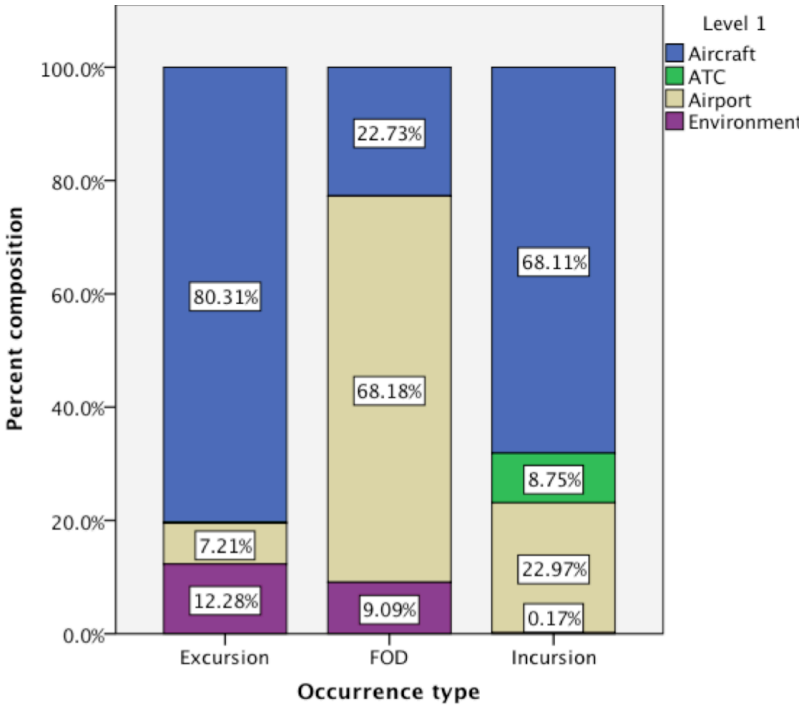


Figure 62: Causal factors (Level 1) per occurrence type U.S.

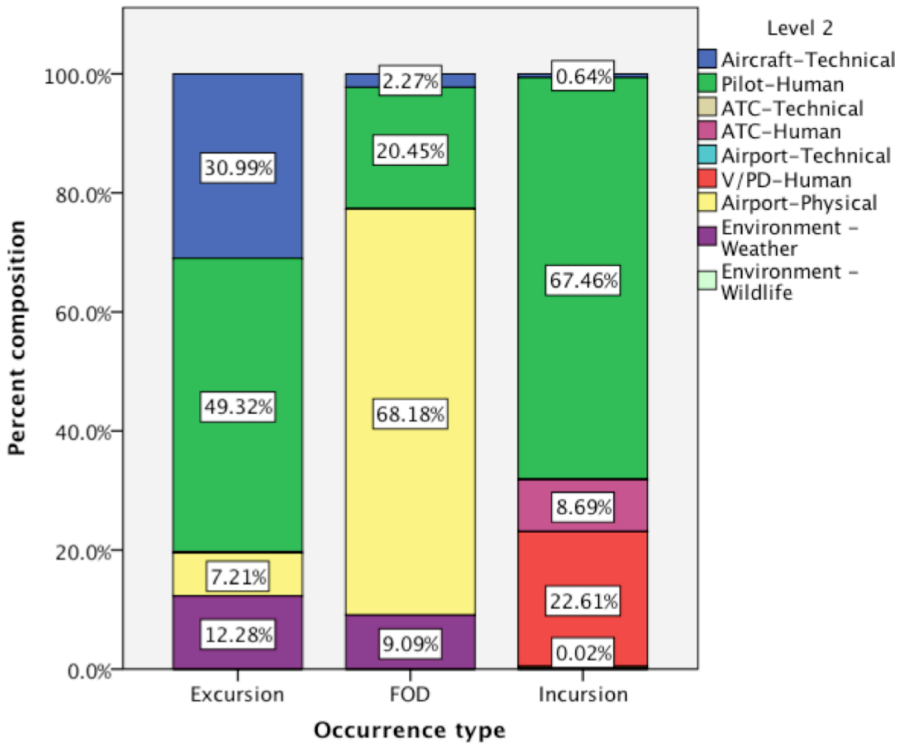


Figure 63: Causal factors (Level 2) per occurrence type U.S.

Figures 62 and 63 indicate that excursions are mostly caused by aircraft technical failures, pilot-related factors, airport physical characteristics and weather. While similar factors were identified for FO(D) occurrences, their distribution however differs, with the category of airport physical characteristics tending to dominate. For the majority of FO(D) occurrences, the reports stated only the type of FO that was found on the manoeuvring area, but not its source. Thus, these occurrences are coded as objects that were present on the surface. Whereas technical and environmental factors cause the occurrence of excursions and FO(D), incursions mainly arise from human-related factors, i.e. pilot, ATC, and V/PD. The identified factors summarised at a high level correspond overall to those identified during the literature search.

Comparisons of causal factors at the stakeholder level are difficult, because databases from only two different stakeholders (regulator / ANSP and ground handling company) were collected for the U.S. In addition, the SHEBBA database is limited to a sample of only 32 relevant U.S. occurrences.

Figures 64 and 65 compare the causal factors across databases and indicate that the stakeholders capture different parts of the taxonomy template.

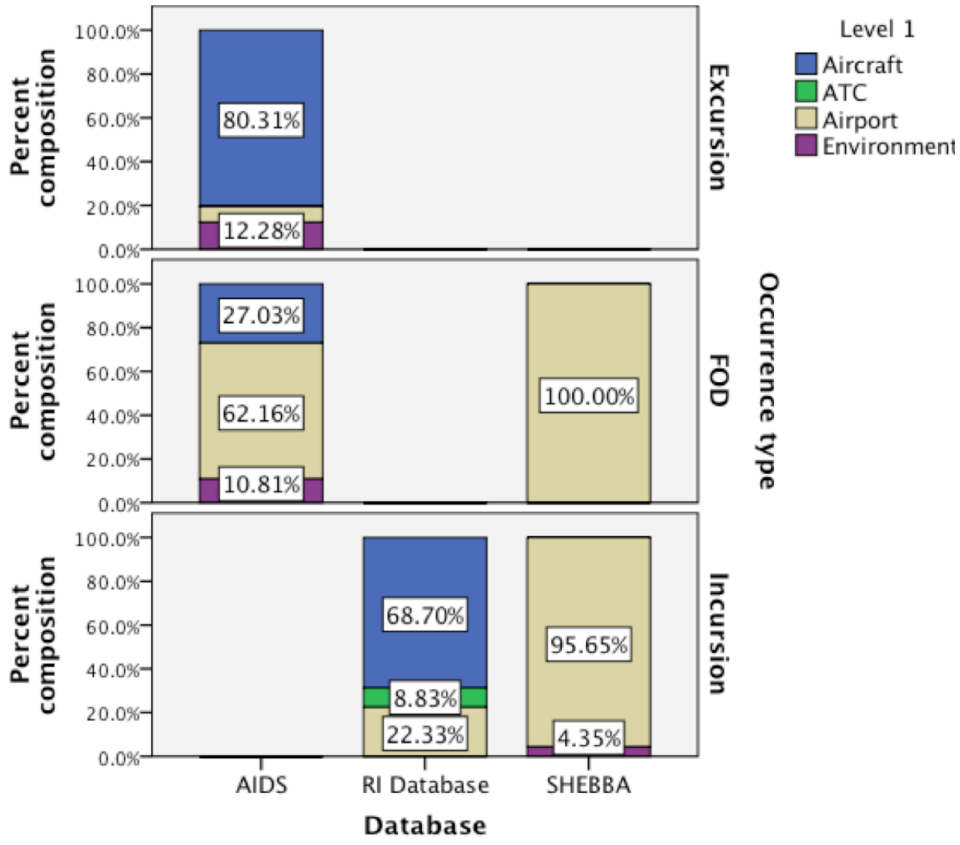


Figure 64: Causal factors (Level 1) per occurrence type per database U.S.

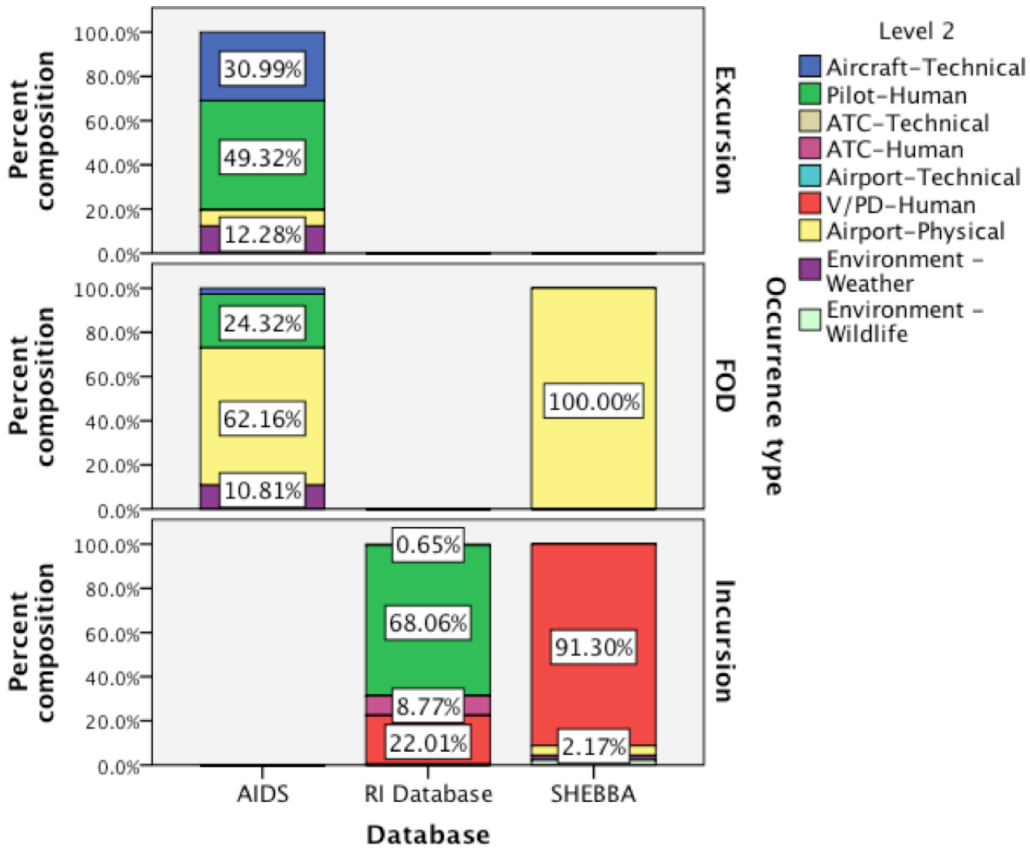


Figure 65: Causal factors (Level 2) per occurrence type per database U.S.

For FO(D) occurrences, SHEBBA captures only airport related factors, whereas AIDS identifies, in addition, aircraft technical failures, pilot-related factors and weather. Similarly, incursions captured in the ground handling data (SHEBBA) are (at over 90.0%) predominantly caused by V/PD, whereas the RI database also identifies pilot and ATC-human related factors. These variations are a result of the stakeholder perspective captured by the owner of the database. Ground handling personnel are V/PD who if they report i) are involved in an occurrence, or ii) observe a situation that might challenge safety while they carry out their work, mostly on the apron. In these situations they are surrounded by other V/PD and, therefore, are for example, unaware of ATC failures.

Although the amount of available data is limited, it indicates that, in general, the various stakeholders capture different occurrence scenarios and associated causal factors. This depends on their responsibilities / tasks at the airport.

When analysing the data at the third taxonomy level, the RI database, which captures incursions only, shows pilot human-reliability related factors as being the most frequent cause of occurrences (45.9%). This is followed by V/PD human-reliability related factors (20.1%). The AIDS database, used to analyse excursions and FO(D), also shows pilot

human-reliability as the most frequent causal factor category (41.3%), followed by aircraft technical failures (28.0%). SHEBBA on the other hand, captures predominantly V/PD human-reliability related factors (64.1%). In addition, 13.2% of SHEBBA's factors capture causes related to surface conditions. As introduced in Chapter 3, it is the airport operator's responsibility to maintain the surface and, thus, such data is of interest for the airports. These figures highlight the impact of humans on the occurrence of accidents and incidents, especially human-reliability related factors. The detailed analysis of the causal factors summarised on the third level of the taxonomy is shown in Appendix V Table 3. The analysis also identifies the stakeholder responsible for each of the causal factor categories.

Table 31 shows the causes identified most frequently for each database and the percentage of accidents / incidents according to the particular causal factor.

Table 31: Top 10 causal factors per database U.S.

Stakeholder	Database	Top 10 causal factors
FAA	RI Database	1. Pilot entering runway without authorisation (39.4%); 2. Pilot correct readback, followed by an unauthorised manoeuvre (28.5%); 3. V/PD entering runway without authorisation (19.1%); 4. Pilot not stopping at the required position in front of a runway (hold line) (18.9%); 5. Pilot entering taxiway without authorisation (15.5%); 6. V/PD entering taxiway without authorisation (15.5%); 7. Pilot not stopping at the required position on the manoeuvring area (12.8%); 8. Pilot took off without clearance (8.8%); 9. Pedestrian unauthorised on the manoeuvring area (7.5%); 10. Pilot landed or departed on the wrong / closed runway (7.5%)
FAA	AIDS	1. Aircraft technical failure (9.1%); 2. Aircraft engine failure (8.6%); Aircraft brakes failure (8.6%); 4. Long landing (7.7%); 5. Pilot loss of control over the aircraft while on the runway (6.3%); 6. Runway contamination (6.0%); 7. Aircraft landing gear malfunction (5.3%); 8. Pilot allowed the aircraft to veer off the runway (4.9%); 9. Aircraft tires / wheels malfunction (4.6%); Short landing (4.6%)
Signature	SHEBBA	1. V/PD entering taxiway without authorisation (43.8%); 2. Pedestrian unauthorised on the manoeuvring area (25.0%); 3. V/PD inattention (9.4%); Other FOD / debris on a taxiway (9.4%); V/PD entering runway without authorisation (9.4%); 6. Cargo dollies, baggage carts, etc. breaking loss and start rolling (6.3%); V/PD not stopping at the required position on the manoeuvring area (6.3%)

Following the analysis of individual causal factors, the subsequent paragraphs examine those occurrences for which two causal factors were extracted from the occurrence reports. This was the case for a total of 1,100 accidents / incidents.

Figure 66 shows that the majority of factor combinations are within the same class of causal factors. This includes situations where, for example, a pilot makes two mistakes (e.g. correct read back followed by an unauthorised manoeuvre, followed by not stopping at the required position in front of a runway (hold line)). Only 6.8% of occurrences showed an interaction between stakeholders and / or components of the airport surface system (e.g. physical infrastructure, environment - weather).

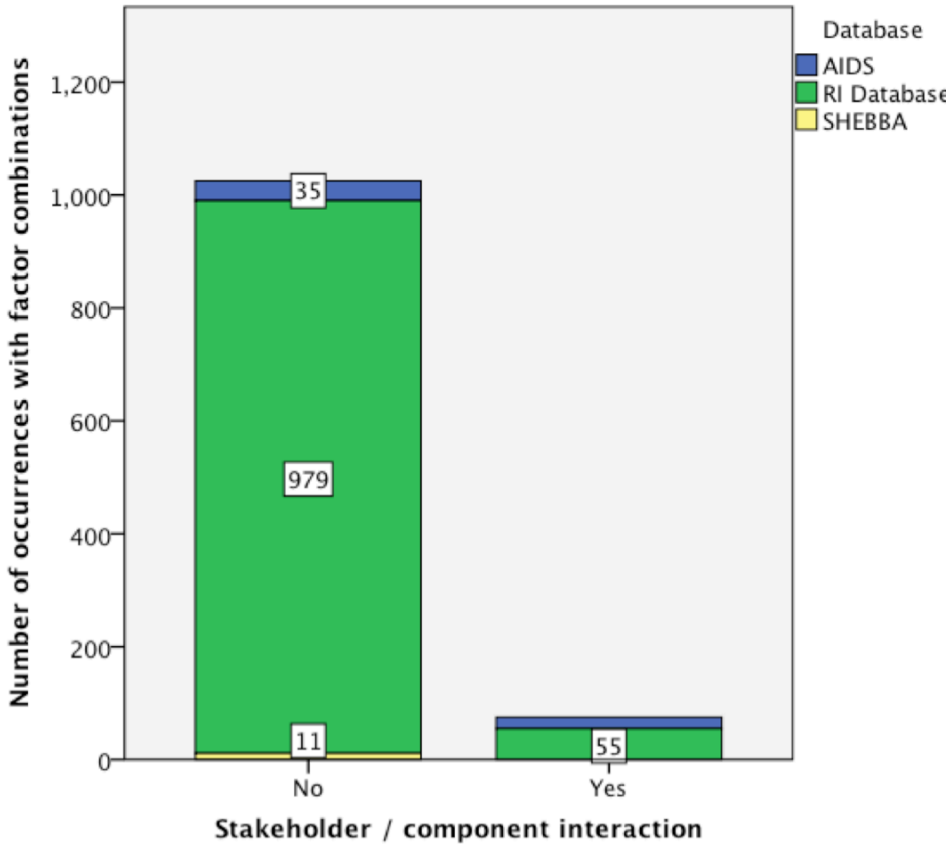


Figure 66: Factor combinations – stakeholder / component interaction U.S.

The most frequent stakeholder / component interaction occurred between pilots and ATC, followed by the influence of the environment on pilot performance. Ranked third is an interaction between pilots and V/PD. Overall, the results show that occurrences do result from interactions between stakeholders and / or other components of the airport

surface system. Therefore, it is important to assess all components of the airport surface system and their interactions as required by the SMS. Figure 67 summarises the results.

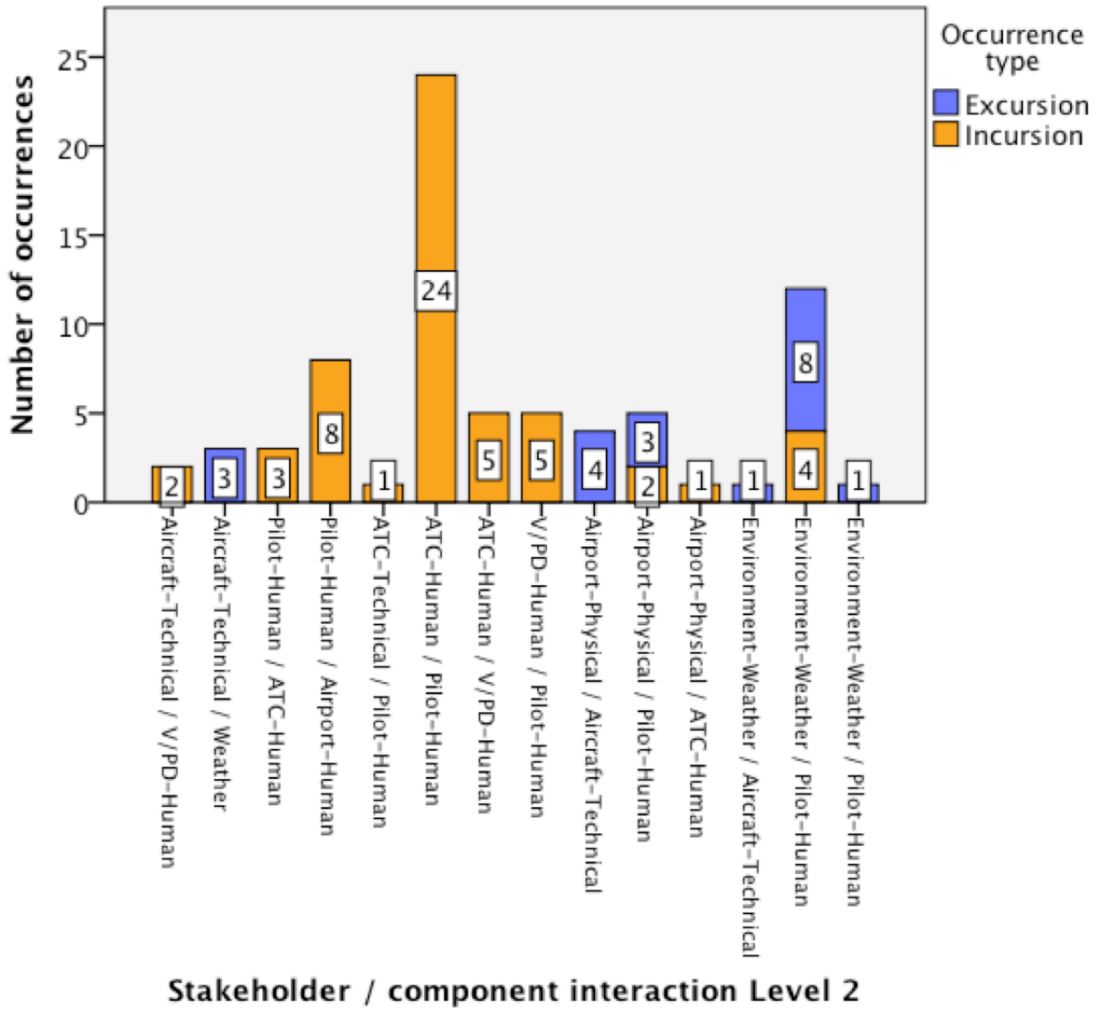


Figure 67: Factor combinations (Level 2) U.S.

7.2.4 Comparison of Stakeholder Viewpoints

The occurrences reported by both Signature and the FAA were compared to determine whether their descriptive narratives convey the same information. Most occurrences in Signature's SHEBBA database were reported between 2010 and 2012. Since no data from the FAA was available for this time period, only the reports from 2007 to 2009 could be used for the comparison. Just one incident reported in 2007 was identified in the Signature database, whereby a refueler became disorientated while driving on the ramp and infringed onto a taxiway. Although this was a surface incident, it was not captured in the FAA

database. Therefore, no conclusions can be drawn from the U.S. data on whether different stakeholders represent different viewpoints.

7.2.5 Examination of Relationships

The analysis presented in the previous sections has indicated the possibility of relationships between occurrence types, causal factors, and stakeholders. Therefore, the data was tested for associations between the type of stakeholder and the occurrence types (Figure 68). There was a significant association between stakeholder and occurrence type X^2 (2) = 117.061, p < .001. However, Chi-Square assumes that the expected frequencies should be greater than five, although it is acceptable in large contingency tables to have up to 20.0% of expected frequencies below five (Field, 2009). With 33.3% of cells having an expected count less than five the test assumptions are not satisfied. In addition, Cramer's V = .187, p < .001 indicates only a weak relationship between stakeholder and occurrence type (Fletcher, 2008). Since the results violate the test assumptions, they are invalid and cannot be relied upon.

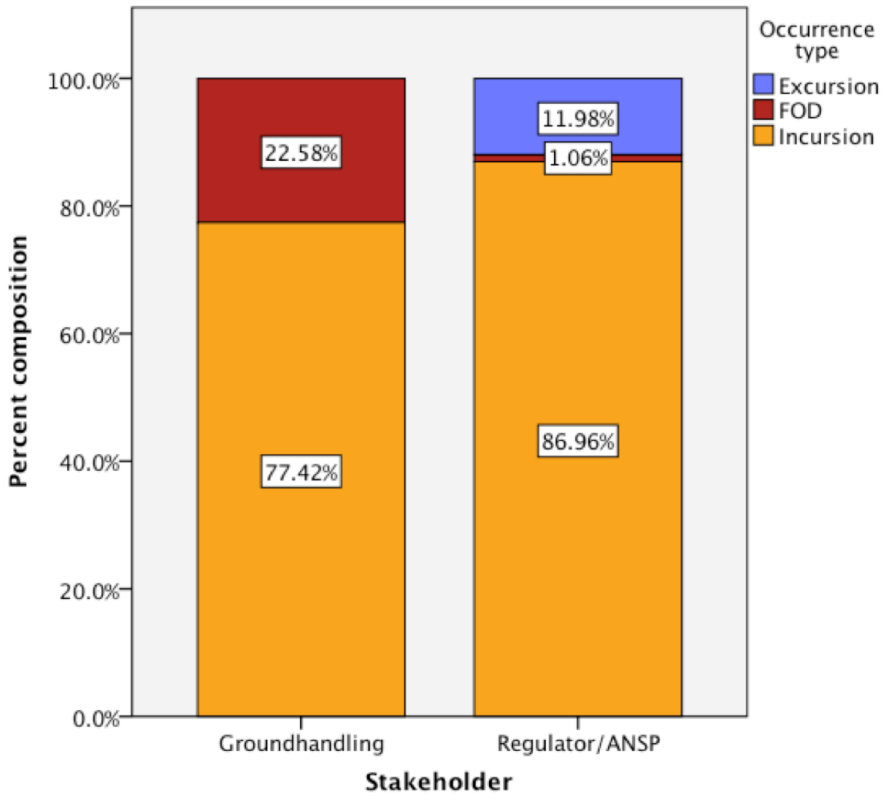


Figure 68: Occurrence type per stakeholder U.S.

Subsequently, the data was tested for associations between stakeholder type and the causal factors extracted from the occurrence reports of each database (Figure 69).

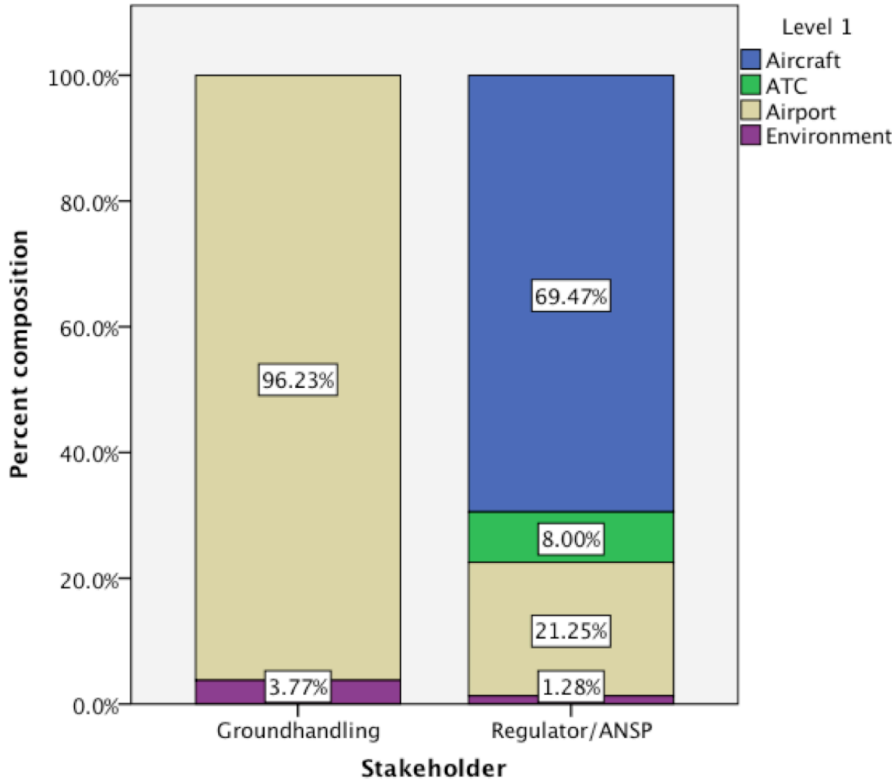


Figure 69: Causal factors (Level 1) per stakeholder U.S.

There was a significant association between the type of stakeholder and the causal factors on the first taxonomy level X^2 (3) = 178.206, p < .001. However, the Chi-Square test assumptions were again not fulfilled, with 25.0% of cells having an expected count less than five. Again, Cramer's V = .175, p < .001, indicates only a weak relationship between stakeholders and causal factors. Hence, the test results are invalid.

The data was also analysed for interactions between occurrence type and causal factors (Figure 70). There was a significant association between the occurrence type and the causal factors at the first taxonomy level X^2 (6) = 714.004, p < .001 and Cramer's V = .247, p < .001 indicates a moderate strength to this relationship.

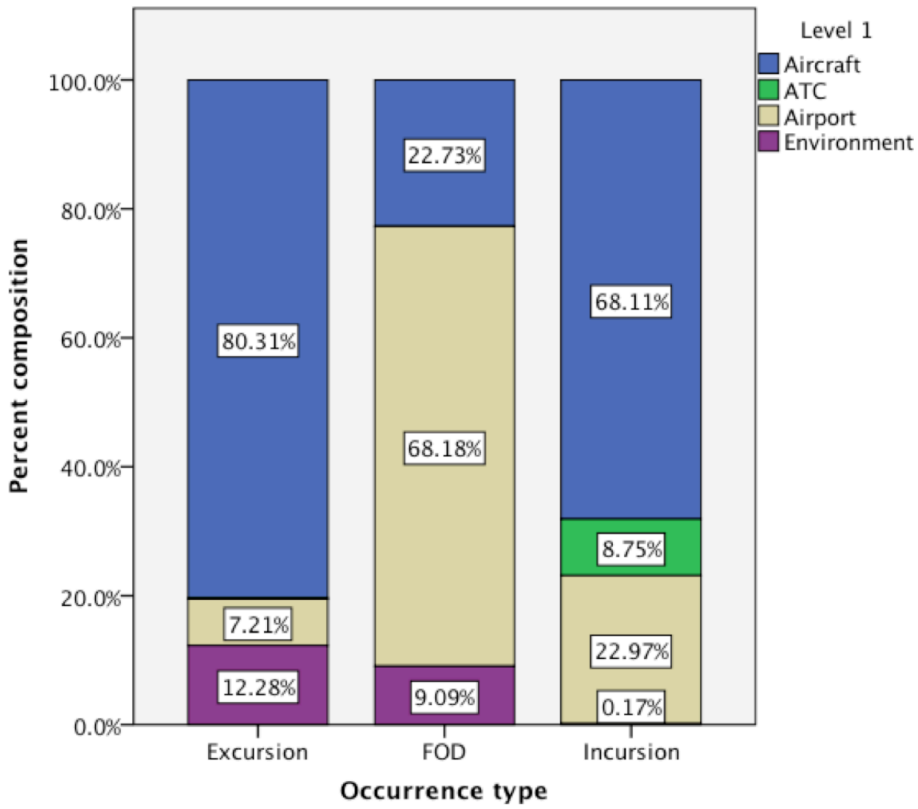


Figure 70: Causal factors (Level 1) per occurrence type U.S.

The associations between causal factors and airports were analysed using the example of the RI database. This database was chosen since the number of occurrences captured in AIDS and SHEBBA at the airport level were too low to be used for statistical analysis.

The results indicate a significant association X^2 (717) = 1660.223, p < .001. However, with 74.2% of cells having an expected count less than five the assumptions of the Chi-Square test are violated. When excluding the causal factors category with the lowest frequency, i.e. environment (0.1% of causal factors), the test assumptions are not fulfilled (X^2 (38) = 1498.454, p < .001, with 65.6% of cells having an expected count of less than five). Finally, the data of the top 20 airports that reported the highest number of incursions (per 100,000 movements) was used to repeat the test, but nevertheless the data remained insufficient to support such analysis (X^2 (38) = 158.775, p < .001, with 46.7% of cells having an expected count of less than five).

In conclusion, it is not possible to test whether there is an association between airports and causal factors. The number of reported incidents (and therefore causal factors) is too low to support an analysis at the airport level.

7.2.6 Interviews

Interviews with pilots were conducted to complement the safety data analysis and to get an insight into the causal factors from the pilot perspective in North America. This was due to the problems to collect data from a U.S.-based airline as discussed in Chapter 6 section 6.3.1.

- **Method**

The aim was to explore the causal factors underlying airport surface safety occurrences from the perspective of U.S. pilots. A semi-structured interview approach using open-ended questions was chosen. Semi-structured interviews cover a list of themes and questions, which may be varied from interview to interview. Questions can be omitted during the flow of conversation or additional questions can emerge. This approach is flexible and useful for exploratory analysis and thus suitable for this research. The interviews were conducted on a one-to-one basis (Saunders*, et al.*, 2007).

To introduce the research context, pilots were given a short overview on the research topic and the objective of identifying the causal factors to airport surface safety occurrences. To fulfil the fifth research objective (i.e. to identify the causal factors underlying airport surface safety occurrences) it was necessary to ask only one question:

What, from your perspective, are the reasons why occurrences on the airport surface may happen?

In a first round of data collection four chief pilots were interviewed during a Runway Safety Action Team (RSAT) meeting at a major U.S. airport. Chief pilots are senior persons responsible for ensuring that an airline's operations are conducted in compliance with the regulations. Therefore, these pilots had a sufficient level of experience to guide the further interviews.

To collect more data the FAA and a major U.S. airport authority were asked to recommend airlines known for a good safety culture that could be approached. The SMEs advised contact with a major low-cost carrier known for its efforts to promote safety in the industry. This airline operates flights to over 80 destinations in the U.S and allowed access to its crew room under a condition of confidentiality and anonymity. Interviews were conducted randomly on an ad-hoc basis, i.e. every pilot who entered the crew room was approached and notes of each interview were taken and later analysed.

- **Results**

In total, twenty pilots were interviewed, including five chief pilots and one training pilot, to explore the causal factors underlying airport surface safety occurrences from the perspective of U.S. pilots. Pilots were interviewed on a one-to-one basis; although, in one case, two pilots were interviewed together. In total, there were 18 individual interviews, and one with two participants. The pilots' age ranged from 32 to 61 with an average of 46.1 years. Table 32 contains the causal factors stated by the pilots and the frequency they were mentioned. In addition, Table 32 compares the causal factors to the literature and the analysis of safety data presented in this chapter. The new factors identified through the interviews are highlighted in grey.

The interviews revealed causal factors mainly in relation to the manoeuvring area layout, pilot-related factors, ATC human-related factors, communication issues between pilots and ATC, and weather and visibility. The main factors possibly leading to accidents / incidents for the pilots were distraction and periods of high workload.

One issue became apparent during the interviews: when U.S. pilots were asked about causal factors underlying airport surface safety occurrences they immediately associate this with incursions. Even though a brief of the research and its objectives was given, all conversations drifted towards a discussion of causal factors underlying incursions. Overall, incursions seemed to be the main concern in the U.S aviation sector.

Comparing the factors gathered during the interviews to those from the literature and from the safety data analysis, new ones emerged. These are:

- Multi-tasking job;
- Daydreaming / taking personal problems to work;
- Runway configurations that require frequent communication with ATC;
- Risk mitigation strategies complicate the operations;
- Technology in the aircraft is ten years behind; and
- New technology is not available to commercial pilots.

In particular the third factor, i.e. runway configurations that require frequent communication with ATC, was mentioned by 30.0% of the pilots. This causal factor implies that several runways need to be crossed to reach the final runway. For each crossing the pilot needs to hold short and contact ATC to obtain a crossing clearance. This increases the amount of communication and leads to frequency congestion. When

enquiring whether this is a causal factor specific to the home base airport of the pilots, it was confirmed that this problem can be generalised to U.S. airports. This factor furthermore, indicates that the physical layout of the airport surface impacts on the occurrence of accidents and incidents and this aspect will be addressed further in Chapters 10 and 11.

Table 32: Causal factors based on interviews with U.S. pilots

Causal factor	**Frequency**	**Captured through**	
		Literature	**Safety data**
Manoeuvring area design and complexity	4	✔	✔
Improper taxiway signage	1	✔	✔
Loss of situational awareness	4	✔	✔
Unfamiliarity with the airport	5	✔	✔
Multi-tasking job	1	-	-
Periods of high workload in the cockpit	6	✔	✔
Time pressure	1	✔	✔
Rushed behaviour from last-minute runway changes	1	✔	✔
Distraction	11	✔	✔
Inattention	1	✔	✔
Daydreaming / Taking personal problems to work	1	-	-
Complacency	2	✔	✔
Confusion about what to do	1	✔	✔
Misunderstanding ATC instructions	1	✔	✔
Communication	3	✔	✔
Overlong and complex transmissions	1	✔	✔
Runway configurations require frequent communication with ATC*	6	-	-
Blocked transmissions	1	✔	✔
Language barriers	1	✔	✔
ATC instructions badly enunciated	1	✔	✔
ATC instructions too fast	2	✔	✔
Different accents from ATC across the states	1	✔	-
Confusing ATC terminology / instructions	3	✔	✔
Improper clearances given by ATC	2	✔	✔
ATC giving instructions during high workload periods (e.g. on short final)	1	✔	✔
Improper handling of stop bar lights from ATC	1	-	✔
Weather	1	✔	✔
Visibility	3	✔	✔
Noise	1	✔	-
Risk mitigation strategies complicate the operations	1	-	-
Technology in the aircraft is ten years behind	1	-	-
Technology not available to pilots	1	-	-
* For instance, pilots need to cross three runways to get to their final runway. Before crossing each runway they need to hold short and get clearance from ATC. This significantly increases the amount of communications.			

Key: Factors identified newly through interviews are highlighted in grew.

When comparing the results from the interviews to the causal factors extracted from the European data, national differences become apparent. Whereas the European pilots complained about the physical infrastructure of airports, such as markings, lighting, signage (e.g. 3.0% of causal factors reported for incursions by easyJet), U.S. pilots did not perceive this to be a problem. There may be several explanations for this. The U.S. might have better regulations and in fact a better physical airport infrastructure. On the other hand, the infrastructure may be problematic, but because pilots have been trained in this environment, they do not perceive it as a problem.

- **Observations**

To investigate this further, three European flight crews (i.e. six pilots) were asked during six jump seat flights (as introduced in Chapter 3 section 3.1.4) the reasons, from their perspective, for the occurrence of accidents and incidents on the airport surface. The flights on the jump seat in addition provided the opportunity to observe the problems directly, as pointed out by the pilots. The main concerns of the pilots were:

- Situational awareness;
- Inappropriate, ambiguous, and missing markings and signage;
- The problems associated to markings and signage are intensified in winter, darkness, rain and other low visibility conditions;
- ATC either does not explain taxi routes properly or too quickly;
- Taxi routes and stands are only known after touch down leaving no time to brief the taxi route upfront;
- The airport and ATC give pilots a hard time if they request marshalls, as this causes delays on the manoeuvring area;
- The airport does not provide the pilots with the correct surface condition information;
- Lack of familiarity with the airport / experience;
- Language barriers; and
- ATC behaviour in certain countries.

Particular problems observed by the author during the six flights were:

- ATC did not descend the aircraft appropriately in one flight;

- The ILS was not calibrated properly at one airport. In the opinion of the flight crew there was a mismatch of about 3°;
- Ambiguous signage at the stands of one airport. The assigned parking position was not clear;
- Inappropriate and missing signs for taxiways at one airport; and
- Taxi error at one airport with a very complex layout and a young, inexperienced pilot. No conflict with other aircraft tough.

- **Limitations**

The results of the interviews are limited by the sample of just 20 pilots of which 16 were from the same airline, and therefore work to the same airline procedures. In particular, low-cost carriers operate a tight schedule with short turn-around times and pilots need to comply with the associated company procedures. In addition, all 20 pilots had their home base at the same airport, which meant they were also used to the same ATC operating procedures at their home base. However, there are 64 direct connections to other airports from this home base and hence, the pilots should be exposed to differing operational scenarios at various airports. Nonetheless, future research should interview pilots from different airlines in various locations. Therefore, the list of causal factors is not an exhaustive list of factors; it rather aims to provide an initial insight into the topic from a U.S. pilot perspective.

7.2.7 Wildlife Analysis

The literature review in Chapter 5 showed that the causes for wildlife strikes could only be determined in rare circumstances. In order to investigate wildlife-related occurrences further, the impact of airport location and surrounding land use on wildlife strikes is analysed. The literature review has shown that certain land uses surrounding airports, such as coastline, moorlands, landfills, or land used for agricultural activities, serve as wildlife attractants. However, quantitative studies on the effect of land uses surrounding airports are lacking (Blackwell, *et al*., 2009).

Data on land use surrounding airports was, therefore, collected using Google Earth. A radius of 13 km around the airports was considered, as this equals an airport's wildlife

control zone (International Civil Aviation Organization, 1991). Data for a total of seven variables derived from the literature (see Chapter 5 section 5.2.5.1, Table 20) were collected, including:

- Presence of sea within 13 km (yes / no);
- Presence of a lake / fjord within 13 km (yes / no);
- Presence of a river within 13 km (yes / no);
- Presence of forested land within 13 km (yes / no);
- Presence of mountainous terrain within 13 km (yes / no);
- Presence of fields within 13 km (yes / no); and
- Presence of residential areas within 13 km (yes / no).

The data was coded as binary variables (0, 1) reflecting the presence, or absence of each land use characteristic. Other variables identified in the literature as possibly influencing wildlife activities at airports (e.g. presence of industry, parks, entertainment facilities) were excluded, as it was not possible to collect reliable data over Google Earth.

To limit the amount of data, the analysis was carried out for the U.S. Northeast only. The U.S. Northeast was chosen as it is characterised by its coastline and a mixture of very dense urban areas and rural areas. Data for 55 airports was extracted from the FAA Wildlife Strike Database (Federal Aviation Administration, 2012b). As wildlife strike reporting is voluntary in the U.S., the percentage of wildlife strikes represented in this database cannot be determined.

Relationships between a continuous variable (i.e. normalised number of wildlife strikes) and a discrete, or true, dichotomous variable (i.e. presence of airport surrounding land use) can be analysed using the point-biserial correlation coefficient (r_{pb}). A dichotomous variable is a categorical variable with only two categories. A discrete, or true, dichotomy is one for which there is no underlying continuum between the categories, for example, a specific surrounding land use is present or not. The point-biserial correlation coefficient is calculated using the Pearson's correlation with the dichotomous variable coded as 0 and 1 (Field, 2009).

A one-tailed test was chosen for the analysis, since it was assumed that the presence of a certain type of land use increased the normalised number of reported wildlife strikes. However, in order to see whether this assumption is correct, the analysis was also carried out using two-tailed tests. Table 33 shows the point-biserial correlation coefficients for the U.S Northeast.

Table 33: Correlation coefficients wildlife strike analysis U.S. Northeast

Variable	**U.S. Northeast n = 55**
Presence of sea	r_{pb} = -.170; Sig. (2-tailed) .197; r_{pb} = -.170; Sig. (1-tailed) .099
Presence of lake	r_{pb} = -.208; Sig. (2-tailed) .113; r_{pb} = -.208; Sig. (1-tailed) .057
Presence of river	r_{pb} = -.122; Sig. (2-tailed) .357; r_{pb} = -.122; Sig. (1-tailed) .178
Presence of forest	r_{pb} = .152; Sig. (2-tailed) .251; r_{pb} = .152; Sig. (1-tailed) .125
Presence of mountains	Variable is a constant
Presence of field	r_{pb} = -.061; Sig. (2-tailed) .645; r_{pb} = .061; Sig. (1-tailed) .322
Presence of residential area	Variable is a constant

No correlations were identified between the land use surrounding the airport and the normalised number of reported wildlife strikes. However, to conclude from this that there is no relationship between the airport surroundings and wildlife occurrences could be misleading. The possible reasons for not identifying significant relationships include:

- The wildlife data is likely to be underreported;
- The analysis considered only strike data, however, strikes are a random phenomenon, therefore an analysis using bird count data might come to different conclusions; and
- The analysis considered only risk factors, but did not take control measures initiated by the airports into account (i.e. airports may be aware of their wildlife risk and have therefore put mitigation measures into place).

Future research should address these issues.

7.2.8 Conclusions United States

The following conclusions can be drawn from the analysis of the U.S. data:

- Occurrence rates may be influenced by safety campaigns that promote safety awareness and a just culture;
- The occurrence types have different causal factors associated with them;

- The percentage of reported accidents / incidents where stakeholders and / or system components interact is low, but sufficient to show that occurrences can be caused by such interactions. Therefore, all system components and their interactions need to be assessed following the concept of SMS;
- There is an indication that the stakeholders collect different occurrence types. However, the results need to be confirmed through further statistical testing;
- Similarly, there is an indication that the stakeholders capture different causal factors, but again further testing is needed to confirm these results;
- Stakeholders capture causal factors that lie within the responsibility of other parties, and which therefore might be useful for these parties.

7.3 United Kingdom

7.3.1 Data Overview

For the UK three databases, representing the regulatory (UK CAA MORS), airline (easyJet AQD), and ground handling (Signature SHEBBA) perspectives were analysed. Table 34 shows the data in overview.

Table 34: Data overview occurrences UK

Stakeholder / database	Geographical location	Number of occurrences					Number of airports involved	Considered time period
		IN	EX	FOD	WL	Total		
Regulator / MORS	UK	539	279	66	154	1038	255	2009 - 2010
Airline / AQD	Europe	69	1	75	-*	145	46	2005 - 2010
Signature / SHEBBA	UK	37	0	31	3	71	11	2007 – April 2012

* The wildlife data was excluded from further analysis for reasons explained in Chapter 6 Section 6.6.5.

7.3.2 Occurrence Rates

For the data provided by the UK CAA, normalisation data (i.e. movements per airport per year) was available only for the 50 biggest airports in the UK. For 205 mainly smaller

regional airfields no movement data was available. Nevertheless, a total of 327 accidents / incidents (i.e. 31.5%) occurred at these smaller airports and some experienced a very high number of accidents / incidents, with up to 15 occurrences within two years. Furthermore, with only two years of data available, a trend could not be established. For these reasons, occurrence rates from the MORS database are not shown.

Among the 50 airports for which normalisation data was available the highest number of occurrences (per 100,000 movements) happened at airports with movements below the national average. Occurrences in this context refer to the total of incursions, excursions and FOD. The wildlife data has not been considered since, at 154 occurrences, the number of wildlife strikes seems low. Overall, the findings confirm the results from the analysis of the U.S. data, that less busy airports in terms of traffic movements experience a higher rate of occurrences.

Figure 71 shows the reported number of occurrences (per 100,000 movements) for easyJet. The figure shows the occurrence of incursions, excursions and FOD from 2005 to 2009.

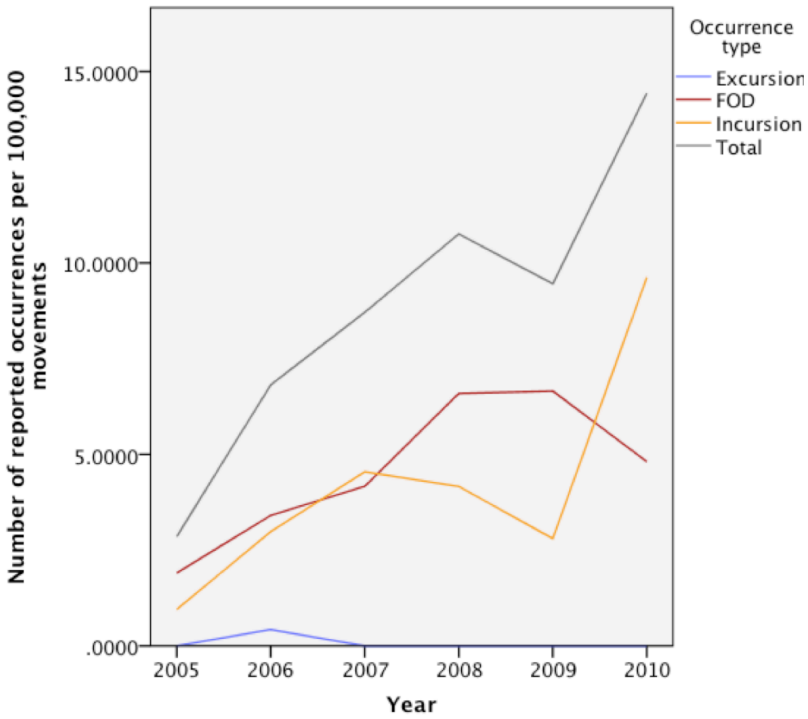


Figure 71: easyJet reported number of occurrences (per 100,000 movements)

As can be seen, the trend increased over the time period considered with the total number of occurrences tripling. This is due to the airline's business expansion. easyJet was

established in 1995 and grew to a fleet of 189 aircraft servicing over 130 destinations by 2013 (easyJet plc, 2013). Structured communications with the safety data providers revealed further explanations for this picture. Fluctuations in the number of occurrences are not only associated to easyJet's expansion, but also to the opening of new routes to destinations in countries that are not always compliant with the International Air Transport Association's (IATA) recommendations. In addition, more operations to seasonal airports were offered. These airports tend to invest less in infrastructure and operations due to the seasonal nature of their business and, consequently, limited profit opportunities (Structured communication with easyJet plc Safety Analysts and Investigatiors, July 2011). In addition, the company actively promotes a culture of open reporting of occurrences, which may have impacted the reporting level over time.

For the airline, the highest number of occurrences was reported for destinations to which the airline has flown irregularly in the past. Therefore, the normalised number of occurrences is heavily influenced by the small number of movements and should not be generalised. The top five airports with the highest number of occurrences are shown in Appendix V (Tables 4 and 5) for each database, including the total number of movements per airport and their normalised number of occurrences.

Structured communications with safety experts working at a major UK airport revealed that a fluctuation in terms of number of occurrences is also considerably influenced by the underlying procedures and operational practices. For example, a vehicle driver at a major UK airport, who does not use the airport surface on a regular basis, i.e. daily, has to book him / herself a slot on the manoeuvring area with the ATC tower. Once the vehicle is cleared, the clearance is valid for a whole day and the vehicle driver is free to go everywhere (except active runways). Vehicles that use the airport surface on a daily basis are automatically cleared. In contrast, vehicle drivers at other airports have to be cleared for every single movement they undertake on the airport surface. This concept of 'free-range' implies that incidents such as a vehicle driver being on the taxiway without clearance barely exist at some airports. This influences the number of reports (Structured communication with Safety Manager of a major ground handling company at Heathrow Airport, 2011). Free range operations are practiced worldwide.

There was no operational data available to normalise the safety data from Signature.

7.3.3 Frequency Analysis

This section presents the results of the analysis of causal factors. The findings refer to incursions, excursions and FO(D) occurrences. Wildlife strikes are analysed subsequently. A total of 2,260 causal factors were extracted from the safety data and Table 35 shows their distribution across the three databases. Figures 72 and 73 show the distribution of causal factors across occurrence types summarised on the first and second levels of the taxonomy, respectively.

Table 35: Data overview causal factors UK

Stakeholder	Database	Number of occurrences analysed	Number of critical factors extracted	Number of different critical factors extracted from each database
UK CAA	MORS	884	1936	294
easyJet	AQD	145	226	92
Signature	SHEBBA	68	98	34

As seen before, Figures 72 and 73 highlight that the different occurrence types have different causes. Comparing the results to the U.S., the UK data shows that environmental factors (e.g. poor visibility, adverse weather, reflecting sun) can lead to an incursion. Such factors were not captured in the U.S. databases. In addition, airport physical characteristics, such as inadequate markings, lighting and signage, were reported causes for incursions. Again, the U.S. FAA data did not record these factors. The causal factors underlying excursions and FOD are, to a large extent, the same as those reported in the U.S., though they differ in terms of their frequencies. For FO(D) occurrences, the UK data shows that V/PD human-related factors contribute to occurrences. This was not possible with the U.S. data as they were not recorded.

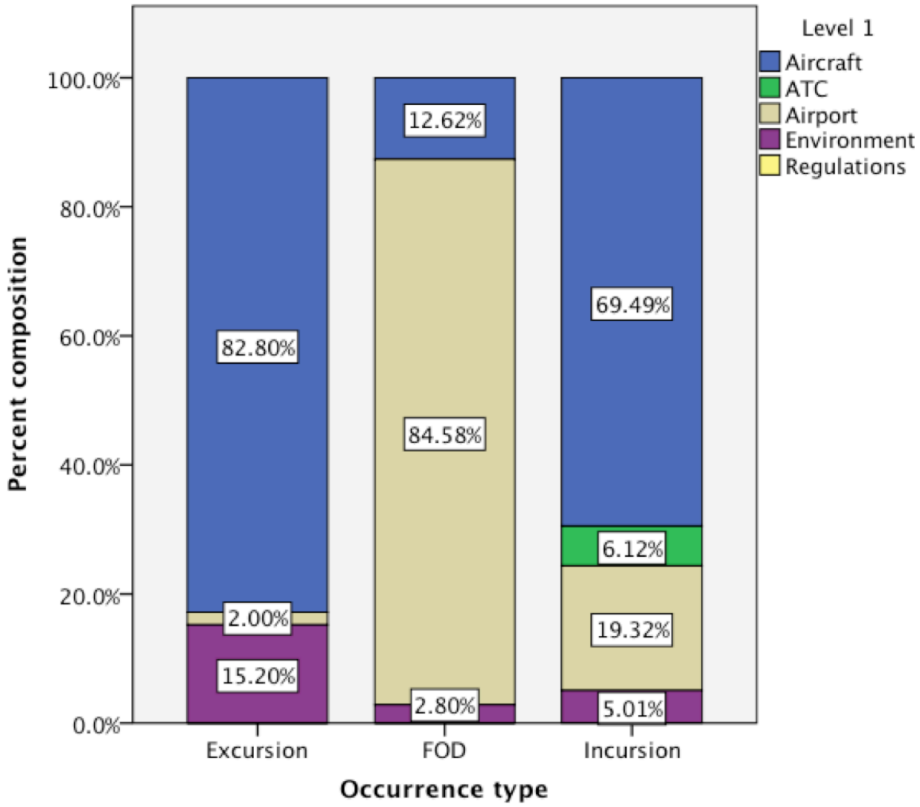


Figure 72: Causal factors (Level 1) per occurrence type UK

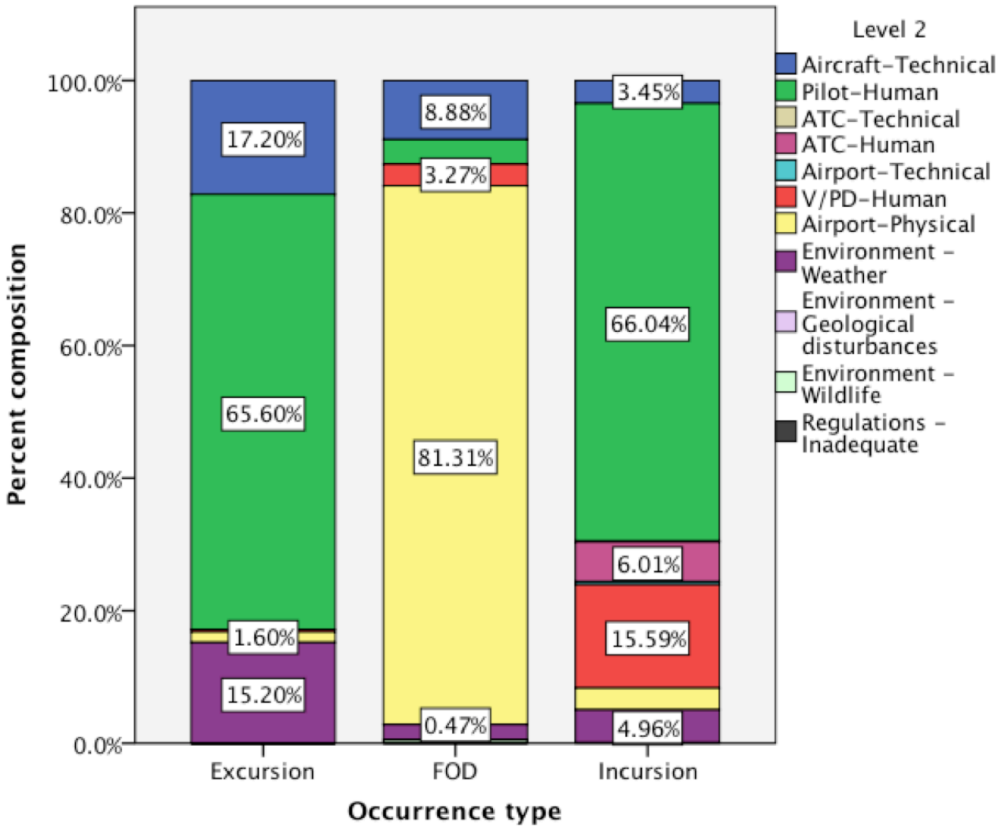


Figure 73: Causal factors (Level 2) per occurrence type UK

Analysing the data by stakeholder (Figures 74 and 75), it can be seen that the regulator captured environmental factors as causes for incursions. This shows that stakeholders of the same type (in this case, regulators) can capture different causal factors. Similarly, the regulatory database in the UK (MORS) showed V/PD human-related factors as causes for FO(D), which were not present in the U.S. FAA data.

There may be two explanations for the variation of causal factors across countries. The variations may be caused by national or geographical differences, or the reporting system. In this case, the latter is more probable as environmental factors, such as reflecting sun and low visibility conditions, exist in both countries. This indicates that the level of detail captured in occurrence reports varies, which in turn influences the causal factors. In fact, the database with the higher DQI (MORS) captured the greater variety of causal factors. This again supports the statement made in Chapter 6, i.e. that it is worth investing into high quality data.

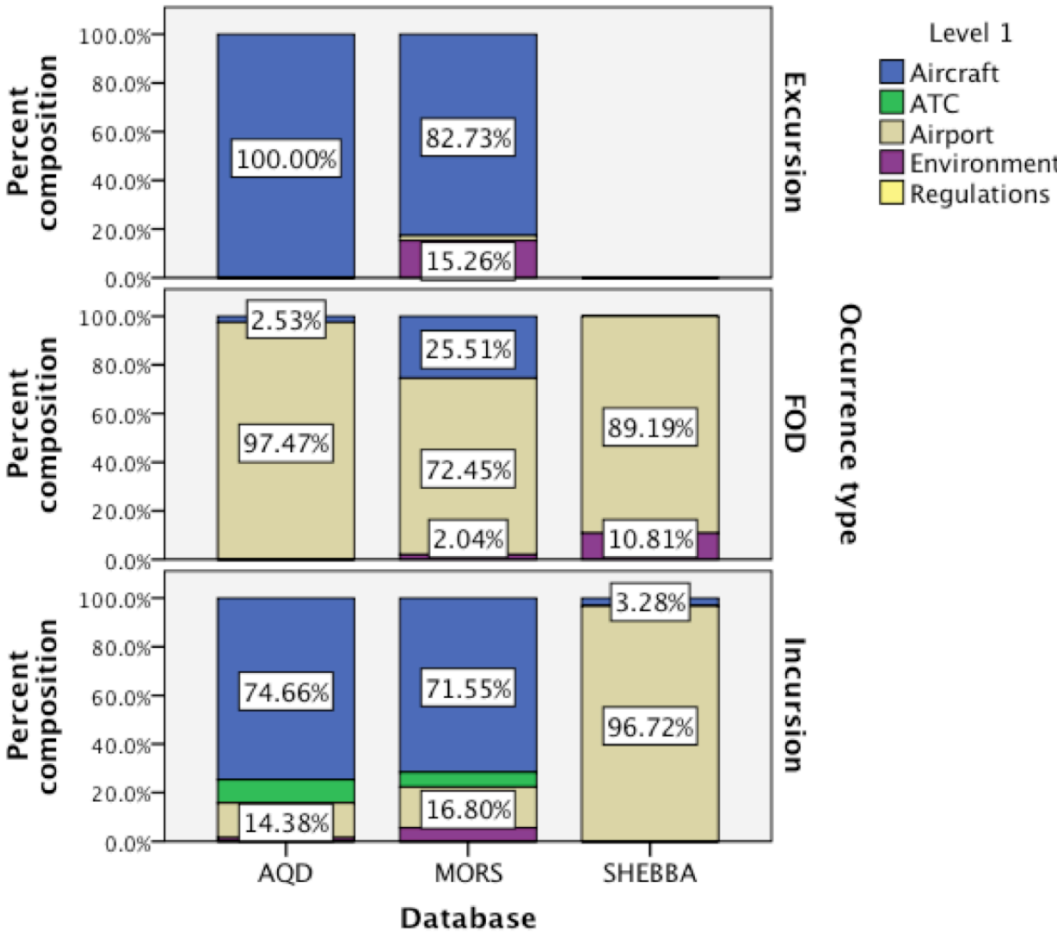


Figure 74: Causal factors (Level 1) per occurrence type per database UK

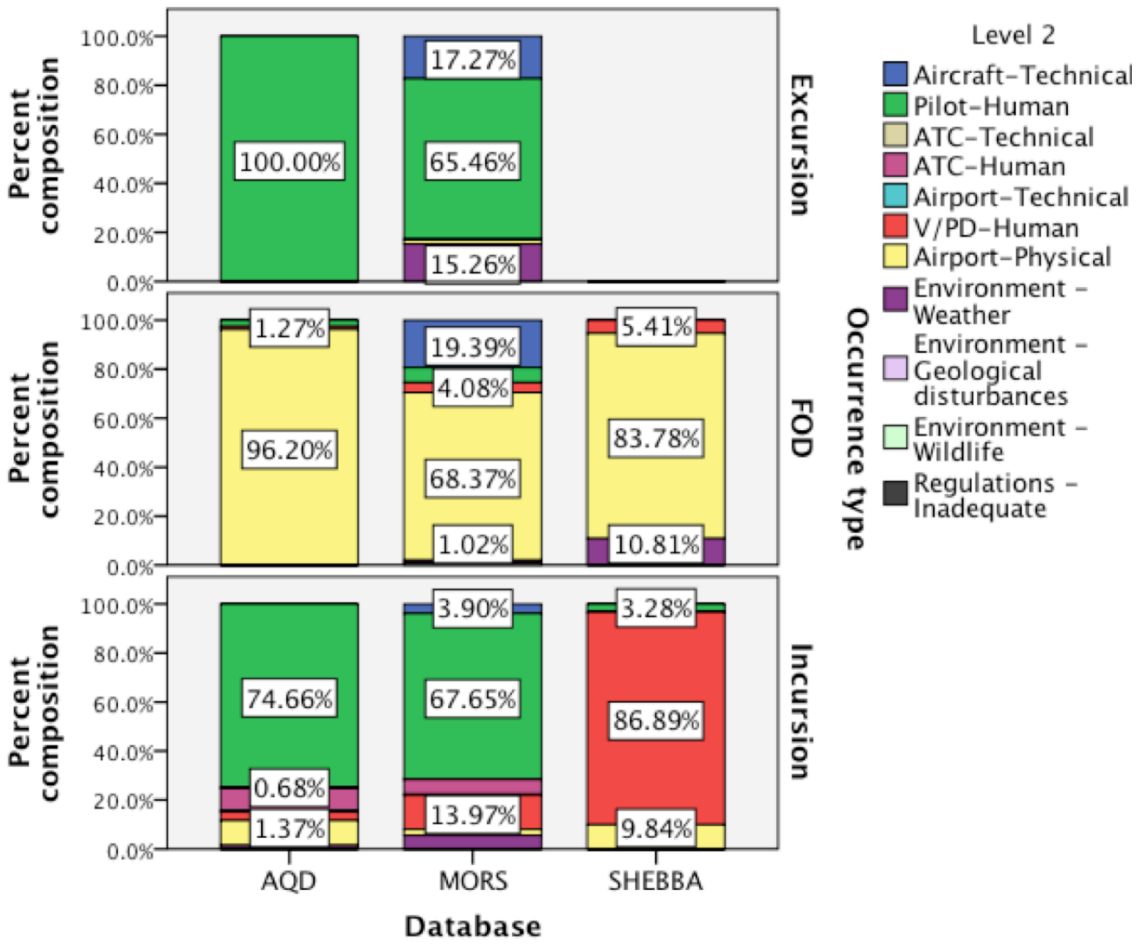


Figure 75: Causal factors (Level 2) per occurrence type per database UK

The V/PD human-related factors were in addition identified as causes for FO(D) in the SHEBBA ground handling databases. Comparing these factors to the U.S. findings allows conclusions to be drawn on a lower causal level. That is, the causal factors differ across the countries even within one organisation (i.e. Signature), which could be a result of the reasons stated above (i.e. national or geographic differences).

Comparing the data across the three stakeholders (i.e. regulator, airline and ground handling company), it can be seen that the various parties capture different causal factors. For example, the airline data does not capture environmental factors as causes for FOD, whereas the regulator identifies the impact of wildlife, and the ground handling company the contribution of weather. Likewise for incursions, the different stakeholders capture diverse perspectives. Whereas the airline and regulator capture predominantly pilot-related factors, ground handling captures mainly V/PD human-related factors, which indicates the different scope of the reporting systems depending on the interests and responsibilities of the concerned stakeholders. Therefore, an airline is predominantly concerned with

occurrences that involve pilots, while ground handling companies mainly collect data that relates to occurrences caused by V/PD.

The highest number of causal factors identified from the MORS database at the third level of the taxonomy are classified as pilot human-reliability related factors (49.2% of causal factors). The analysis is shown in Appendix V Table 6. The most frequent causal factors for the airline fall into the category of runway / taxiway conditions (33.7%), followed by pilot human-reliability related factors (29.2%).

Table 36 shows the most frequent causes at the factors level. The percentages given in the table show the percentage of occurrences to which a particular factor contributed.

Table 36: Top 10 causal factors per database UK

Stakeholder	Database	Top 10 causal factors
UK CAA	MORS	1. Pilot entering runway without authorisation (27.5%) 2. Pilot entering taxiway without authorisation (14.1%) 3. V/PD entering runway without authorisation (12.1%) 4. Pilot loss of control over the aircraft while on the runway (10.1%) 5. Pilot non-compliance with ATC instructions (7.9%) 6. Pilot readback not conform to the issued clearance (6.3%) 7. Wind shear, gusts, other winds (5.9%) 8. Pilot inexperience / student pilot (5.2%) 9. Aircraft landing gear failure (5.0%) 10. Hard landing (4.9%)
easyJet	AQD	1. Other FOD / debris on the runway (19.3%) 2. Pilot not stopping at the required position in front of a runway (hold line) (18.6%) 3. Wildlife remains on the runway (13.8%) 4. Other FOD / debris on the taxiway (4.8%) 5. Pilot entering taxiway without authorisation (4.8%) 6. Pilot not stopping at the required position on a taxiway (4.8%) 7. Pilot entering runway without authorisation (4.1%) 8. Pilot landing without clearance (3.5%)
Signature	SHEBBA	1. V/PD entering taxiway without authorisation (32.4%) 2. V/PD failed to comply with traffic rules and to give way to preceding traffic (11.7%) 3. Other FOD / debris on the taxiway (8.8%) 4. Garbage / rubbish on the taxiway (7.4%) Cargo equipment (e.g. ULD container, palettes) on the taxiway (7.4%) 6. Winds (5.9%) Environmental FOD (e.g. gravel, sand, stones) on the taxiway (5.9%) 8. Blocked stand (4.4%) Parking on the double-white / double-yellow line (4.4%) Pedestrian wilful penetration of the manoeuvring area (4.4%) Pedestrian on the manoeuvring area (4.4%) FOD from an aircraft on the taxiway (4.4%)

It was possible to extract two causal factors for 456 accidents / incidents (i.e. 41.6%), see Figure 76. Of these, 94 occurrences showed an interaction between stakeholders and / or components of the airport surface system.

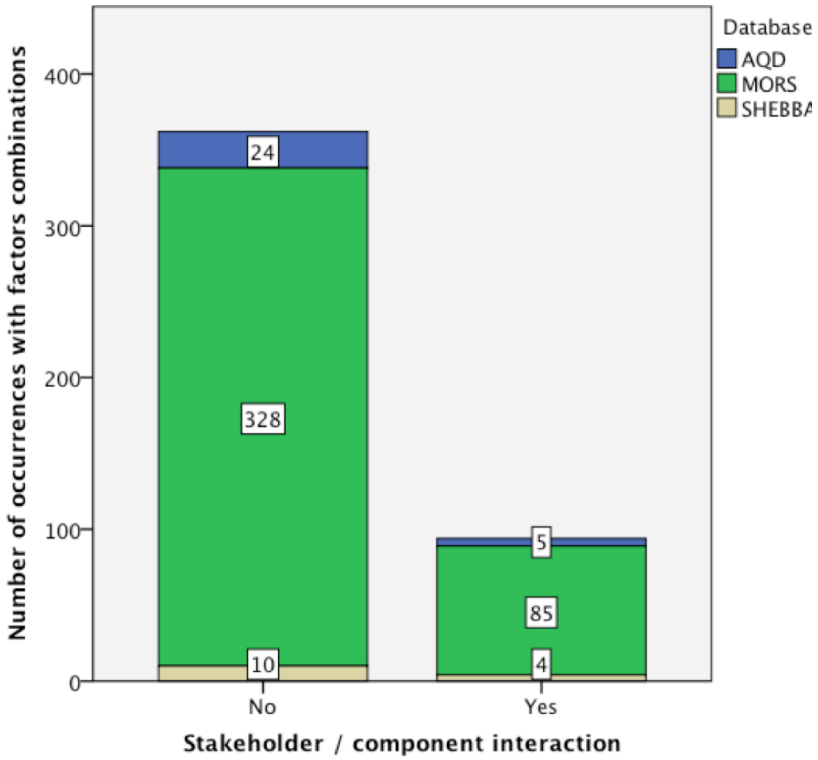


Figure 76: Factor combinations – stakeholder / component interaction UK

The three combinations of interactions between stakeholder and / or other components of the surface system with the highest frequencies are: the influence of weather on pilots, the interaction between ATC and pilots, and V/PD - pilot interactions. These are identical to those identified in the U.S. In addition, situations where aircraft technical failures lead to pilot-human related factors were identified. Figure 77 visualizes the results.

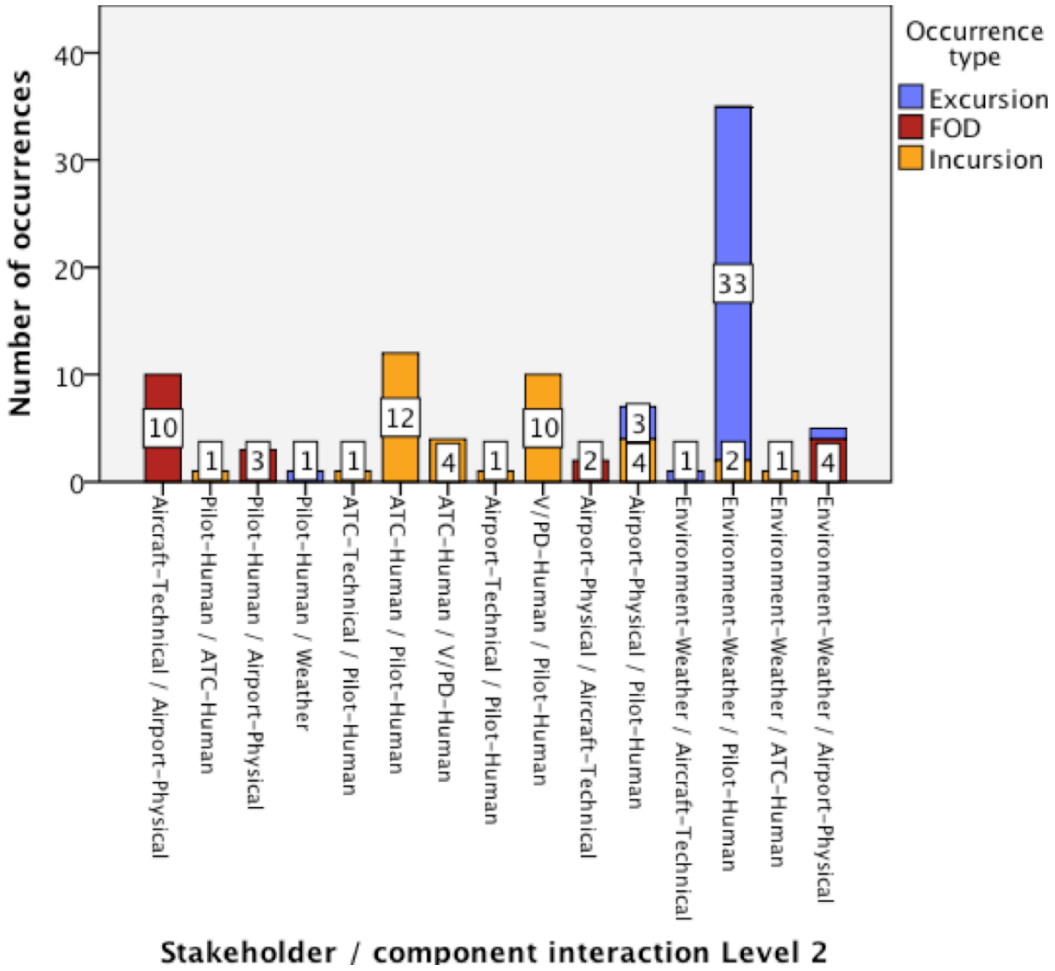


Figure 77: Factor combinations (Level 2) UK

In a next step, the UK CAA wildlife data was analysed. However, for the majority of reports it was not possible to determine why an animal was present at an airport. Only one report out of 154 allowed the extraction of a causal factor. This report referred to a situation where a deer was present on the manoeuvring area due to a hole in the perimeter fence. For the remaining wildlife occurrences, it was only possible to identify the kind of animal that was involved in the occurrence (Table 37).

Two conclusions can be drawn from this analysis. Firstly, the data analysis confirms the findings from the literature review, which showed that it is not possible to identify the causes for why birds and mammals are present at airports. Secondly, the analysis has shown that other animals apart from birds, which have been addressed almost exclusively in the literature, can be present at an airport and can create a hazard. Therefore, more effort should be devoted to recording why animals are present as all mammals have the potential to challenge the safety of surface operations. Thus, an airport surface risk assessment should address all types of wildlife.

Table 37: Wildlife occurrences UK

Animal	Frequency
Bird	139
Cow	1
Deer	7
Dog	2
Fox	2
Rabbit	1
Sheep	2

The same analysis was done using a random sample of 100 occurrences classified as bird strikes in the easyJet data. Again, no causal factors could be extracted from the data. Due to the limited amount of information to be extracted from these occurrences, this data was not analysed further. Also, the three wildlife reports in the SHEBBA database did not contain information regarding their causes.

7.3.4 Comparison of Stakeholder Viewpoints

There was some overlap in the reporting between the three databases, raising the possibility of being able to identify how different stakeholders capture accidents / incidents from different viewpoints. To match the time periods, the AQD and SHEBBA data were first filtered for those occurrences that happened in 2009 and 2010. The reports captured in AQD and SHEBBA were subsequently matched to the MORS data based on the date and location of occurrence. For this analysis the whole MORS database was considered, including accidents / incidents that happened outside the UK.

SHEBBA contains 25 UK occurrences for 2009 / 2010. None of these was found in the regulatory MORS database. Moreover, one of the Signature reports explicitly stated that an easyJet aircraft committed a taxi error. However, this was not captured in the airline data, which indicates underreporting in the airline and regulatory databases.

easyJet's AQD database captured 67 occurrences in 2009 / 2010 of which 15 (i.e. 22.7%) were found in the regulatory MORS database. The wording of the descriptive narratives was not identical in the two databases, since the UK CAA provides its own summary for each occurrence. This CAA summary, however, in general reflected the original report from easyJet very well. In only three out of the 15 cases did the airline provide additional information, representing 20.0% of reports, although one needs to bear in mind the low sample size. The example below shows this.

For instance, a UK CAA report contains the following description: “ATC cleared a/c 1 to vacate RWY onto TWY C and hold at C2 due to a/c 2 pushing back from freight apron onto TWY C. ATC then observed that a/c 1 had passed C2. Action taken to resolve situation.” This narrative allows for the extraction of ‘pilot not stopping at the required position on a taxiway’ as a causal factor.

The airline report states: “On taxi-in we were cleared to 'C2' to hold. On arriving at the point where we thought the 'C2' holding point was, we had actually crossed the holding point by a short distance. At night the 'C2' holding point is not clear. It is not illuminated and with the ground being wet any markings were invisible.” This report allows for the identification of the reasons for crossing the holding point, namely, night-time operations, a wet surface and a lack of lighting.

Overall, the UK CAA data reflects the facts of single reports well. However, there is a large number of occurrences that are not reported into MORS, as the examples from the airline (AQD) and ground handling (SHEBBA) databases show. This underreporting is an important finding, since the UK CAA claims to collect all safety challenging situations. In addition, it has implications for the validity of data collection systems on a multi-national level.

As introduced in Chapter 6, ECCAIRS, for example, collects and analyses safety data from EU States with the objective of improving transport safety. The current analysis has shown that, at a national level, the aviation stakeholders report different percentages of their actual occurrences into the regulatory database, which leads to imbalances. In addition, the analysis indicated that some of the stakeholders fail to report all occurrences, i.e. operational personnel do not report everything. Of the reports that are filed, therefore, only a certain percentage goes into the regulatory database, although the regulator claims that its database contains all situations that might affect safety. This regulatory database is then aggregated on the EU level with other national databases that probably suffer from the same problems.

7.3.5 Examination of Relationships

Following the descriptive analysis the UK data is analysed for relationships between the variables. Firstly, the data was tested for associations between stakeholder and occurrence types (Figure 78). To make the analysis comparable between the three

stakeholders wildlife strikes were excluded. There was a significant association between the type of stakeholder and the type of occurrence X^2 (4) = 266.031, p < .001. Cramer's V = .0348, p < .001 indicates in addition, that this is a strong relationship.

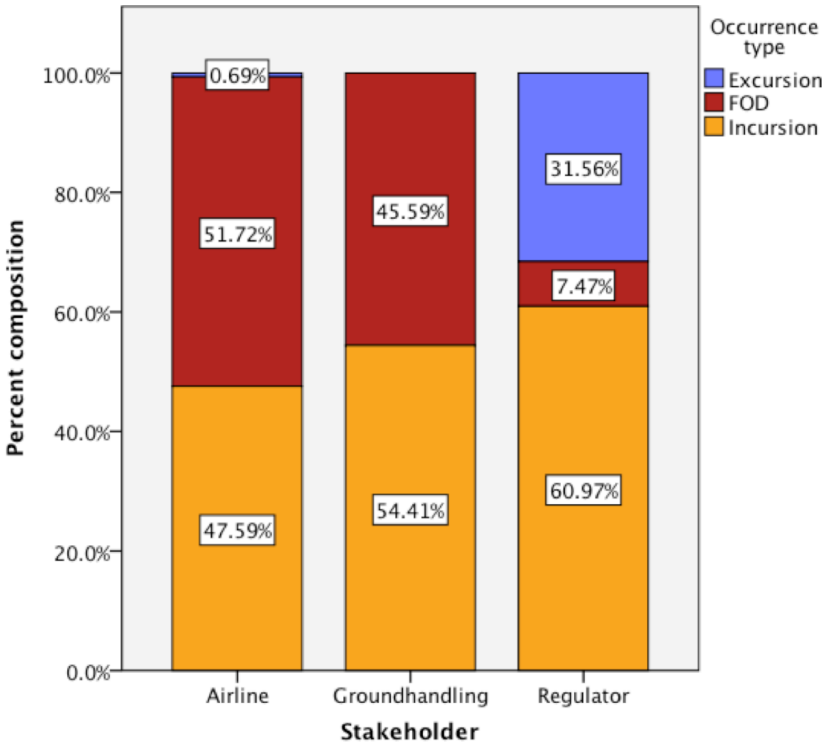


Figure 78: Occurrence type per stakeholder UK

Subsequently the data was analysed for associations between stakeholders and causal factors (Figure 79). In this analysis the causal factors that related to inadequate regulations were excluded because of their low frequency. There was a significant association between the type of stakeholder and the causal factors X^2 = 365.135 (6), p < .001. The Chi-Square test assumptions were fulfilled and Cramer's V indicated a moderately strong relationship with a value of .284, p < .001.

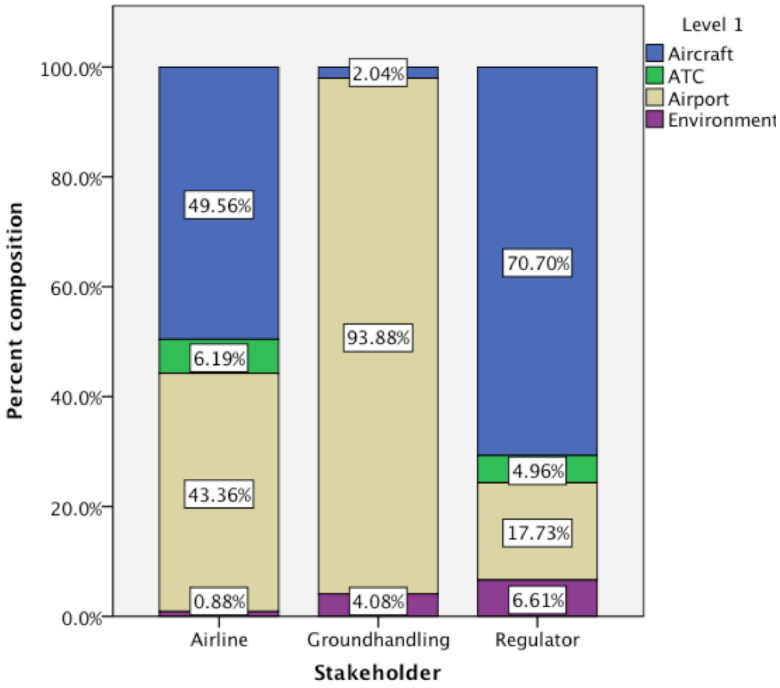


Figure 79: Causal factors (Level 1) per stakeholder UK

Next, the association between occurrence types and the causal factors at the first taxonomy level was analysed (Figure 80), with the results showing a significant association between the variables X^2 (6) = 578.340, p < .001. Cramer's V indicates a very strong relationship with a value of .358, p < .001.

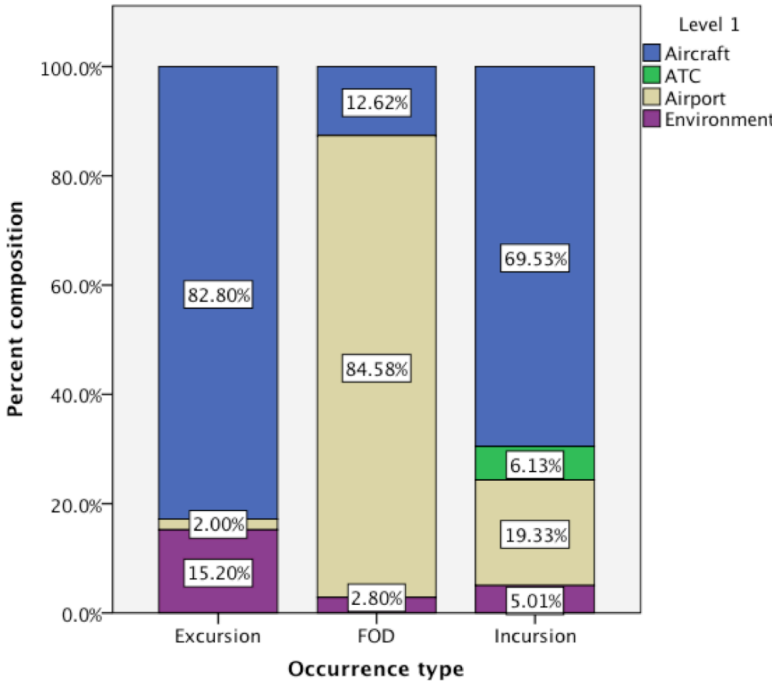


Figure 80: Causal factors (Level 1) per occurrence type UK

In addition, each database was tested individually for associations between occurrence types and causal factors. A significant association was found for the UK CAA MORS data (X^2 (6) = 289.578, p <. 001, Cramer's V = .274, p < .001 – moderately strong relationship). Similar results were obtained using easyJet's data (X^2 (6) = 145.135, p < .001) and the data provided by Signature (X^2 (2) = 7.947, p < .001). However, with 58.3% of cells having an expected count of less than five for the easyJet data, and 66.7% for the Signature data, these two tests violated the assumptions of the Chi-Square test and are, therefore, invalid.

When testing the data at the airport level, i.e. for associations between the causal factors and airports, the same problem as was encountered during the analysis of the U.S. data was identified. The Chi-Square test assumptions were significantly violated because most of the causal factor categories at the first taxonomy level were very infrequently populated. In order to reduce the number of airports, and hence, the number of cells in the contingency table, the analysis was repeated for each database separately. However, this only marginally improved the test results. Overall, associations between causal factors and airports would require a much higher number of occurrences at the airport level.

7.3.6 Conclusions United Kingdom

The following conclusions can be drawn from the analysis of the UK data:

- Small airports (i.e. airports with movements below the national average) seem to have more occurrences reported;
- Different stakeholders capture different occurrence types and causal factors;
- There is an association between occurrence types and causal factors;
- Stakeholders from different countries but of the same type (e.g. regulator) can pick up different causal factors. Therefore, the distribution of causal factors varies across stakeholders of the same type;
- Causal factors underlying wildlife strikes can only rarely be determined;
- There is an underreporting of aviation safety data;
- The aviation stakeholders do not report all occurrences into the regulatory database. The regulatory database is imbalanced due to the varying degrees of reporting;
- The regulatory database does not always contain all available information as to why an accident / incident occurred. In these cases, the complementary airline

report revealed further details, allowing the extraction of more causal factors and a better understanding of what happened and why.

7.4 Norway

7.4.1 Data Overview

Six databases were available for the analysis of the safety of airport surface operations in Norway. The data was provided by the regulator (CAA-Norway ECCAIRS), the ANSP (Avinor-ANSP MESYS), the airport operators (Avinor-Airports MESYS, OSL IFS), and two airlines (Norwegian AQD, Wideroe Sentinel). Therefore, it was possible to overlap the perspectives of four different types of stakeholders. Table 38 shows the data in overview. In contrast to the U.S. and UK, most organisations in Norway (i.e. Avinor-ANSP and Airports, OSL) provided their full database. When pre-processing this data and filtering for relevant occurrences, a small number of collisions was found and included in the analysis.

Table 38: Data overview occurrences NO

Stakeholder / database	Geographical location		Number of occurrences					Number of airports involved	Considered time period
		COL	IN	EX	FOD	WL	Total		
Regulator / ECCAIRS	Norway	6	332	29	125	108	600	54	2008 - 2010
ANSP / MESYS	Norway	0	361	18	10	163	552	21	2008 - 2010
Airport OPR / MESYS	Norway	7	69	9	163	511	759	41	2008 - 2010
Airport OPR / IFS	Oslo	4	155	4	41	19	223	1	2008 - 2010
Airline / AQD	Europe	0	39	2	-	269	310	16	2007 – Oct. 2011
Airline / Sentinel	Scandinavia	1	27	0	-	-	28	15	2008 – June 2012

7.4.2 Occurrence Rates

The number of occurrences (per 100,000 movements) is shown for each database individually. Figure 81 contains the accident / incident trends for the CAA-Norway and Figure 82 for the Norwegian ANSP, Avinor.

The regulatory data reflects a fourfold increase in occurrences from 2008 to 2010. The ANSP data also shows an increase in the number of reported accidents / incidents. In the case of the ANSP, structured communications with the data providers revealed that this is related to safety culture initiatives over recent years and the active promotion of open reporting. In addition, there has been a change in the management with younger people who had safety as part of their education being promoted into key positions. It is argued that this has led to a change in the mind-set in the whole organisation (Structured communication with Safety Investigatiors Avinor AS ANSP, June 2011). As all ANSP-reports are automatically forwarded to the regulator, this development has also influenced the number of reports at the regulatory level.

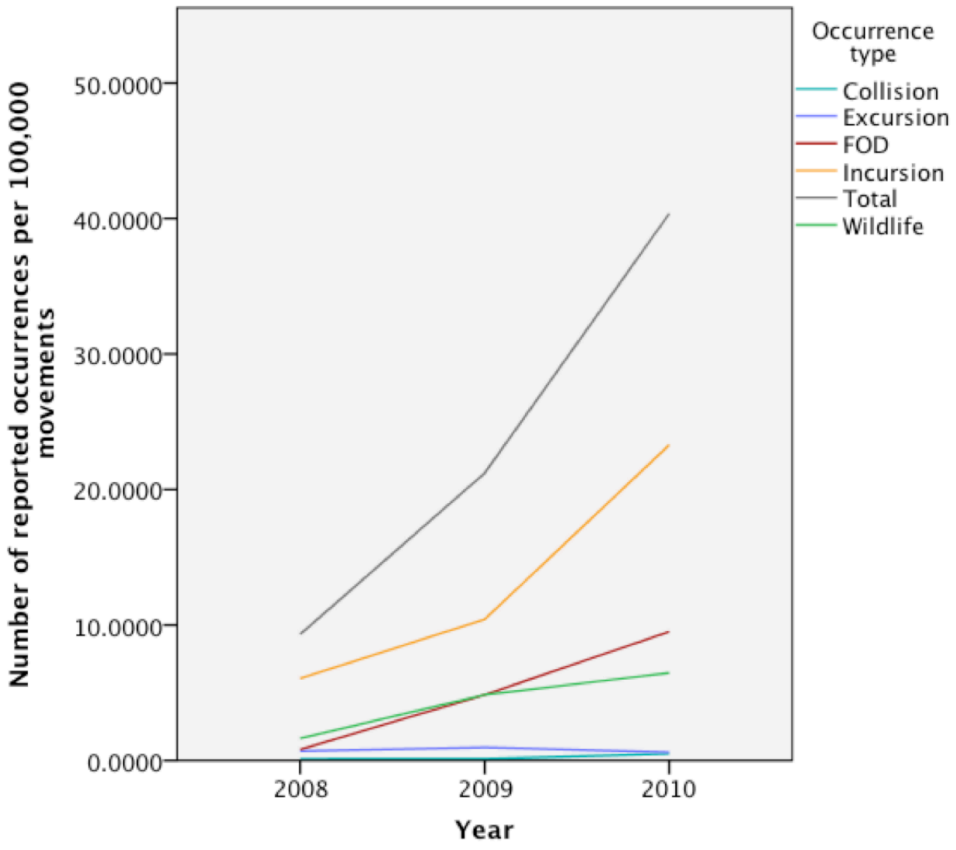


Figure 81: CAA-Norway reported number of occurrences (per 100,000 movements)

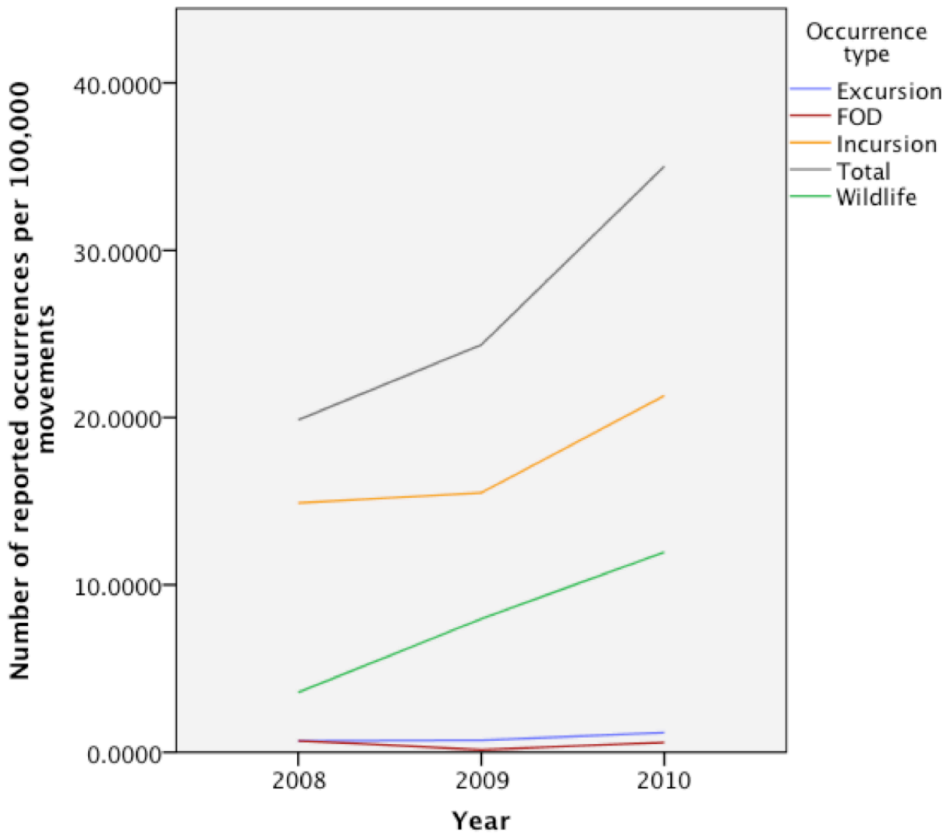


Figure 82: Avinor-ANSP reported number of occurrences (per 100,000 movements)

A similar increasing trend can be observed from the data provided by the Avinor-Airports division (Figure 83). For OSL, the airport operator of Oslo Airport, as shown in Figure 84, the overall trend was a decrease from 2008 to 2010. However, the data shows a 50.0% increase of incursions from 2009 to 2010, which is related to construction work of a new terminal that commenced in 2010.

No normalisation data was available for the two airlines due to sensitivity concerns on their part.

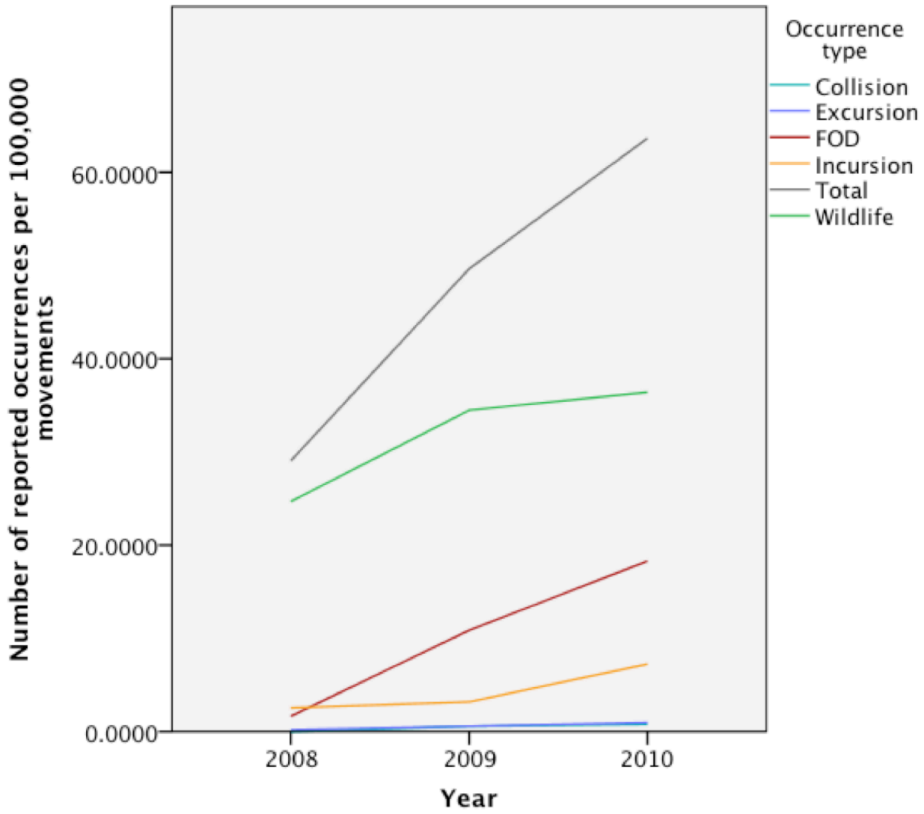


Figure 83: Avinor-Airports reported number of occurrences (per 100,000 movements)

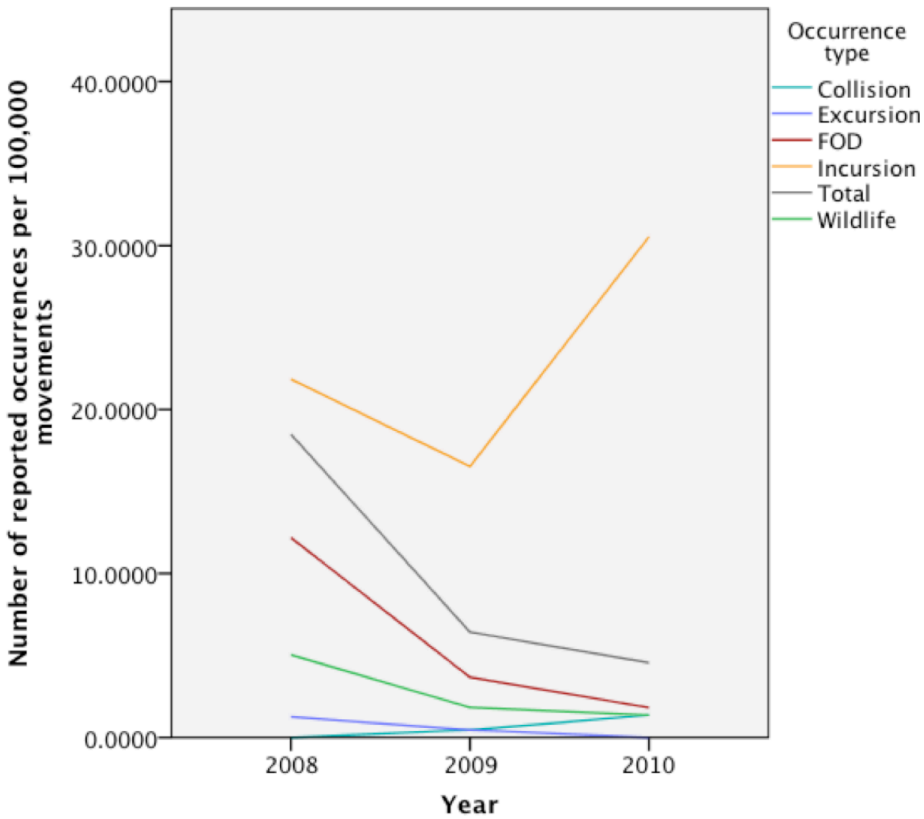


Figure 84: OSL reported number of occurrences (per 100,000 movements)

At the airport level, the regulatory data showed the highest number of occurrences at airports with movements below the national average. This analysis excludes wildlife strikes in order to make it comparable to the other databases. Also, Avinor-ANSP recorded the highest number of occurrences at small regional aerodromes with movements below the national average. Among the top five airports in the Avinor-Airports database, four showed movements below the national average. The analysis is shown in Appendix V Tables 7 and 8. All three databases point to the same problematic airports and structured communications with the safety data providers identified the reasons why small airfields experience a high number of occurrences. The SMEs indicated the following possible explanations for this (Structured communication with Safety Investigatiors Avinor AS ANSP, June 2011):

- The number of general aviation (GA) movements is relatively high at these airports;
- The small number of aircraft movements at these airports leads to inexperience in traffic handling;
- Airport personnel have more time to report than at large and busy airports;
- Some of these airports have a manager with a very strong safety culture and therefore report any situation that deviated from the normal operations;
- There are military activities at some of these airports; and
- A flying school was operating at one of the airports.

7.4.3 Frequency Analysis

This section analyses the underlying causes of occurrences. As before, the analysis of causal factors excludes wildlife strikes, which are assessed subsequently separately. Table 39 provides an overview of the data.

Table 39: Data overview causal factors NO

Stakeholder	Database	Number of occurrences	Number of critical factors extracted	Number of different critical factors extracted from the database
CAA-Norway	ECCAIRS	492	770	199
Avinor-ANSP	MESYS	389	626	183
Avinor-Airports	MESYS	248	402	144
OSL	IFS	204	290	77
Norwegian	AQD	41	96	58
Wideroe	Sentinel	28	52	26

Figures 85 and 86 show the causal factors of each occurrence type, aggregated for the whole country on the first and second level of the taxonomy. Again it can be seen that adding new databases allows the identification of causal factors that are not accessible when fewer datasets are used. For example, the U.S. and UK databases failed to identify ATC-related factors as causes for excursions. On the other hand, the Norwegian data indicates that 2.8% of factors leading to excursions refer to ATC contributions.

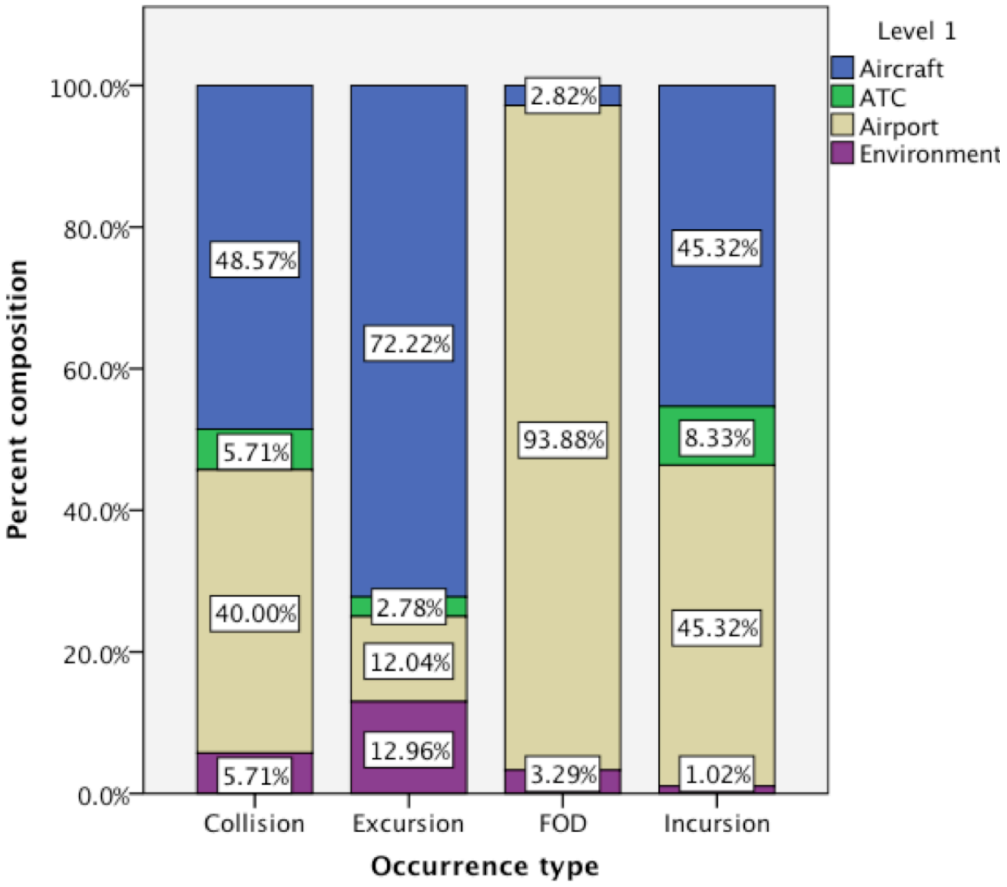


Figure 85: Causal factors (Level 1) per occurrence type NO

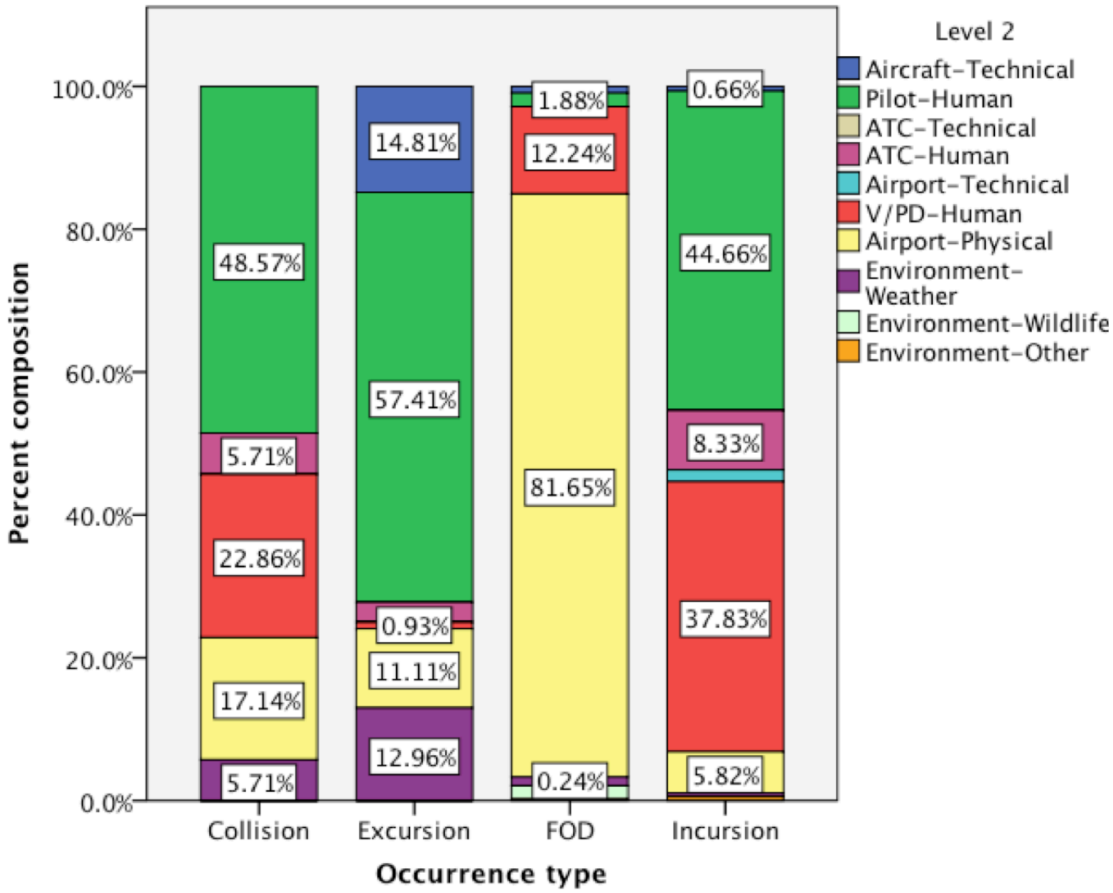


Figure 86: Causal factors (Level 2) per occurrence type NO

The identified collisions were caused by a combination of human-related factors (pilot, ATC, V/PD), and airport physical characteristics, as well as weather. Overall, the causal factors are similar to those identified in the U.S. and UK analyses, but differ in terms of their frequencies. The causes reported for excursions include aircraft technical failure, human factors (pilot, ATC, V/PD), airport physical characteristics, and weather. The causes of FO(D) were identified as aircraft technical failures, pilot and V/PD contributions, airport physical characteristics, and environmental factors (i.e. weather, wildlife, others). The incursions were predominantly due to human-related factors (pilot, ATC, V/PD). In addition, aircraft and airport technical failures, airport physical characteristics and environmental factors contributed to some of the occurrences.

Analysing the data by stakeholder (Figures 87 and 88), it becomes apparent that the ATC contributions to excursions that have been newly identified in the data were for the most part reported by the airline.

Whilst mostly the same causal factors are reported for each occurrence type, their distribution differs across the stakeholders. For example, the airport operator Avinor shows

predominantly V/PD-human factors as causes for incursions, whereas the airlines identified mainly pilot-related factors, and ATC (i.e. Avinor-ANSP) and the regulator (i.e. CAA-Norway) show an approximately equal split between V/PD and pilot-related factors.

Furthermore, the distribution of the causal factors captured by the two airport operators varies, indicating that the causal factors differ at the airport level.

The different frequency distributions of causal factors are a result of the different focus of stakeholders and the nature of their operations. For example, wildlife remains on the surface are the responsibility of the airport operator, but are not a major concern for ATC, unless they cause a disruption to the operations. Thus, certain causal factors are more relevant for the tasks of specific stakeholders. Therefore, they are more likely to be found in the corresponding databases. The distribution of causal factors at the third taxonomy level is shown in Appendix V Table 9.

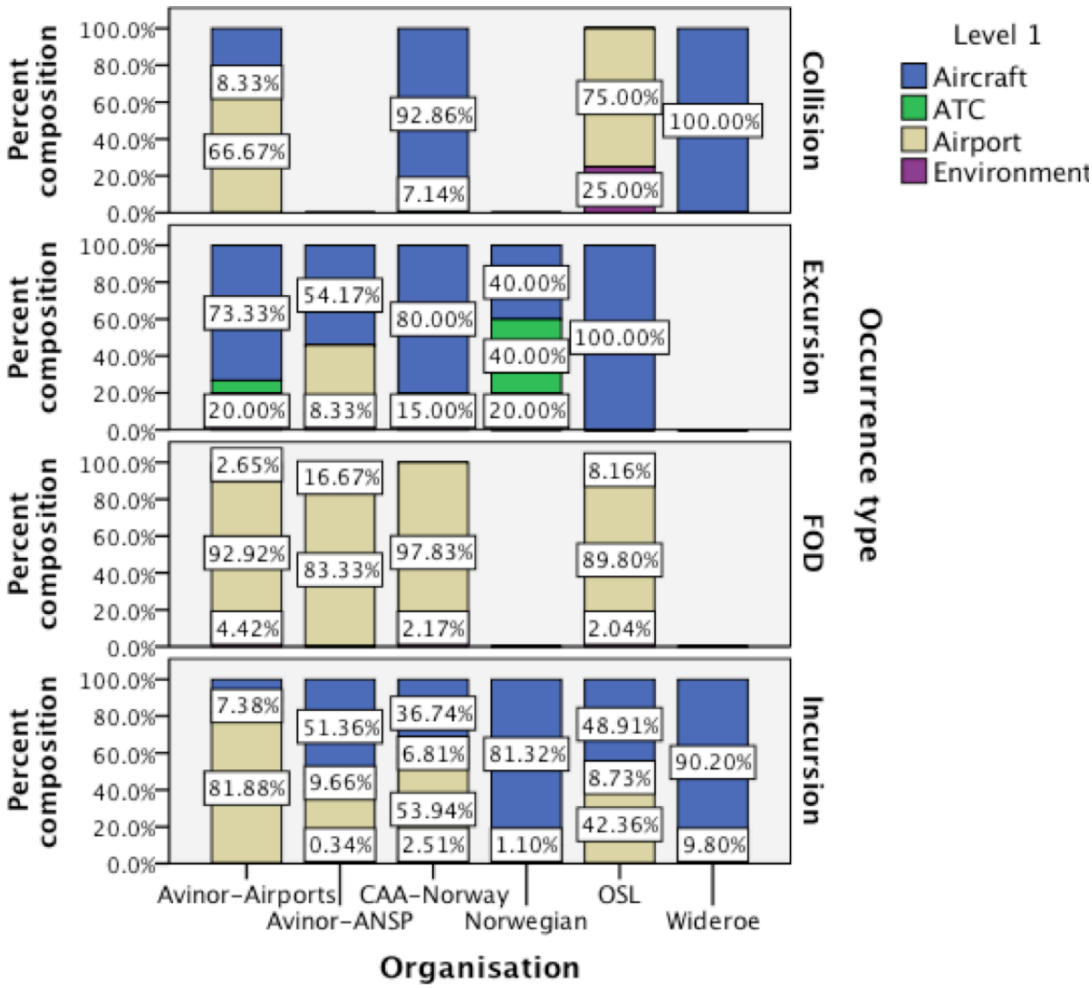


Figure 87: Causal factors (Level 1) per occurrence type per organisation NO

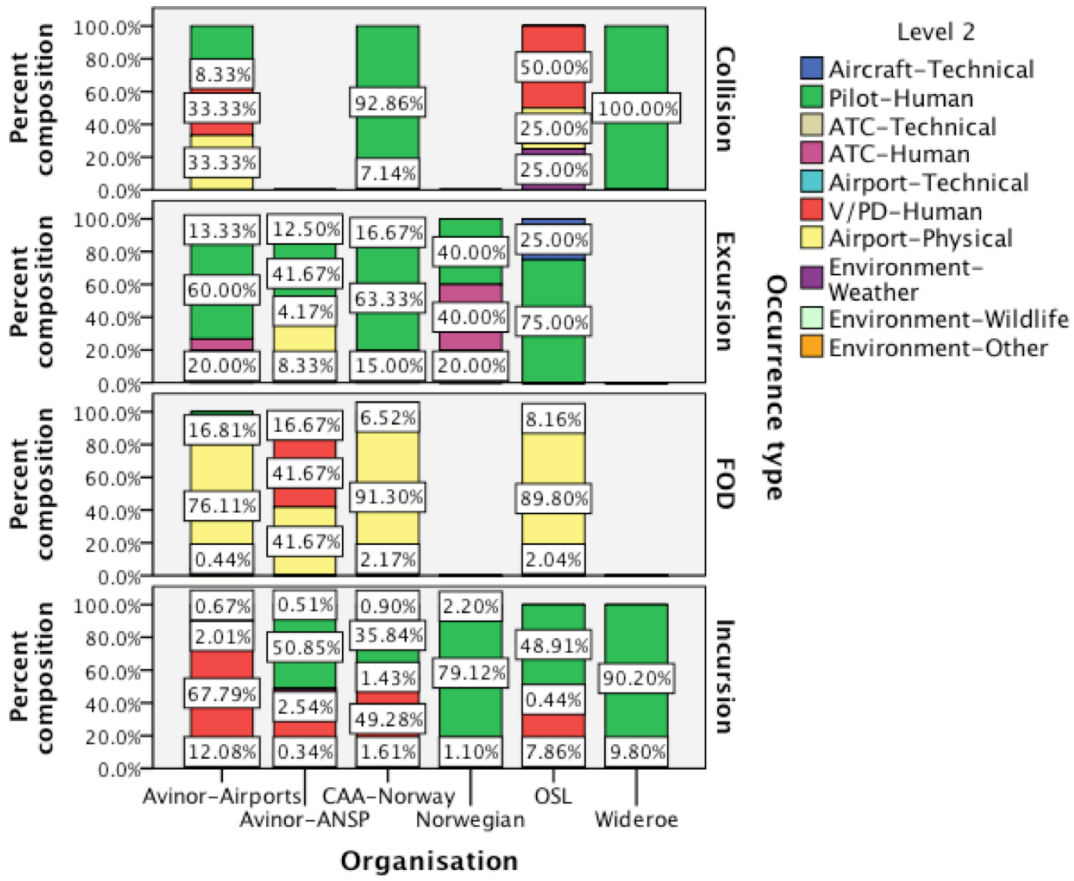


Figure 88: Causal factors (Level 2) per occurrence type per organisation NO

The different focus of stakeholders is also reflected when analysing the data at the level of factors. Table 40 shows the top 10 most frequently identified causal factors for each database. The quantities given reflect the percentage of occurrences caused by a particular factor.

Table 40: Top 10 causal factors per database NO

Stakeholder	Database	Top 10 causal factors
CAA-Norway	ECCAIRS	1. V/PD entering runway without authorisation (12.8%); 2. V/PD entering taxiway without authorisation (10.4%); 3. Pilot entering taxiway without authorisation (9.4%); 4. Pilot not stopping at the required position in front of a runway (hold line) (9.2%); 5. Pilot entering runway without authorisation (7.3%); 6. Maintenance / construction work taking place on the airport surface (6.7%); FOD – Environmental (gravel, sand, stones, etc.) on the runway (6.7%); 8. V/PD no contact to ATC in the first instance to ask for clearance (3.9%); Other FOD / debris on the runway (3.9%); 10. Snow removal operations (3.8%)

Avinor-ANSP	MESYS	1. Pilot entering taxiway without authorisation (22.9%); 2. V/PD entering runway without authorisation (10.5%); 3. Pilot not stopping at the required position in front of a runway (hold line) (9.8%); 4. Pilot took off without clearance (9.0%); 5. V/PD entering taxiway without authorisation (6.9%); 6. Pilot entering runway without authorisation (6.2%); 7. V/PD no contact to ATC in the first instance to ask for clearance (5.9%); 8. Pilot correct read back, followed by an unauthorised manoeuvre (4.9%); 9. V/PD entering the manoeuvring area without authorisation (3.1%); 10. Pilot not stopping at the required position on the manoeuvring area (2.6%)
Avinor-Airports	MESYS	1. FOD – Environmental (gravel, sand, stones, etc.) on the runway (13.3%); 2. V/PD entering runway without authorisation (8.9%); 3. FOD - Tools / small parts on the taxiway (6.9%); Other FOD / debris on the runway (6.9%); 5. FOD – Concrete, asphalt (pavements) on the runway (4.8%); 6. V/PD entering taxiway without authorisation (4.4%); 7. V/PD no contact to ATC in the first instance to ask for clearance (4.0%); Deterioration of infrastructure (4.0%); Other FOD / debris on the taxiway (4.0%); 10. Snow removal operations (3.6%)
OSL	IFS	1. Pilot entering taxiway without authorisation (31.4%); 2. V/PD entering taxiway without authorisation (16.7%); 3. Pilot not stopping at the required position on the manoeuvring area (13.7%); 4. Construction area (3.9%); V/PD entering runway without authorisation (3.9%); FOD – Concrete, asphalt (pavements) on the runway (3.9%); 7. FOD – Environmental (gravel, sand, stones, etc.) on the taxiway (3.4%); ATC forgetting to switch off stop bar lights (3.4%); 9. Snow removal operations (2.9%); Other FOD / debris on the taxiway (2.9%)
Norwegian	AQD	1. Pilot entering taxiway without authorisation (19.5%); Pilot not stopping at the required position in front of a runway (hold line) (19.5%); 3. Pilot took off without clearance (14.6%); 4. Pilot entering runway without authorisation (9.8%); 5. Pilot turned down the volume on VHF/Radio (7.3%); ATC issuing conflicting clearances (7.3%); Pilot landing without clearance (7.3%); Pilot not stopping at the required position on a taxiway (7.3%)
Wideroe	Sentinel	1. Pilot took off without clearance (32.1%); 2. Pilot entering runway without authorisation (17.9%); 3. Pilot misperception concerning a clearance (17.9%); 4. Pilot entering taxiway without authorisation (14.3%); 5. Pilot misapplication of procedures (10.7%); 6. Pilot not stopping at the required position in front of a runway (hold line) (10.7%)

The analysis further identified a total of 432 reports (excluding wildlife), i.e. 30.8% that contained two causal factors. Most of these interactions refer to the same causal factor category. Only 24.8% of the 432 occurrences showed an interaction between the stakeholders and / or other components of the airport surface system (Figure 89). Occurrence reports with stakeholder interactions were, however, found within all databases and Figure 90 presents their frequencies.

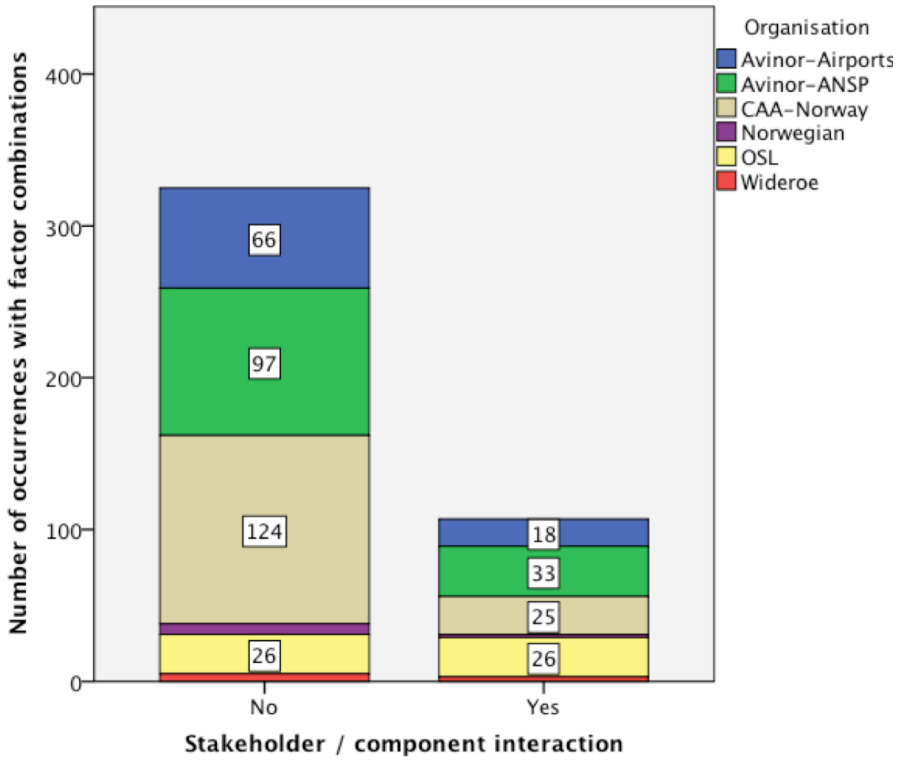


Figure 89: Factor combinations – stakeholder / component interaction NO

The analysis of stakeholder / component interactions reveals national differences. In contrast to the U.S. and UK that have a similar picture, Norway shows the influence of airport physical characteristics on pilot performance as being the highest category of stakeholder / component interactions (26.2%). This figure is approximately 20.0% higher than in the U.S. and UK. These national variations could have several explanations. Firstly, national reporting systems might have failed to capture some of the factors and interactions. Secondly, a particular combination might not exist in another country. Some factors reported for airport physical characteristics are inadequate marking, lighting, and signage. Such infrastructure might not be a problem in other countries. The U.S. pilots for example reported (in section 7.2.6) that they perceived the marking, lighting, and signage at U.S. airports as being adequate.

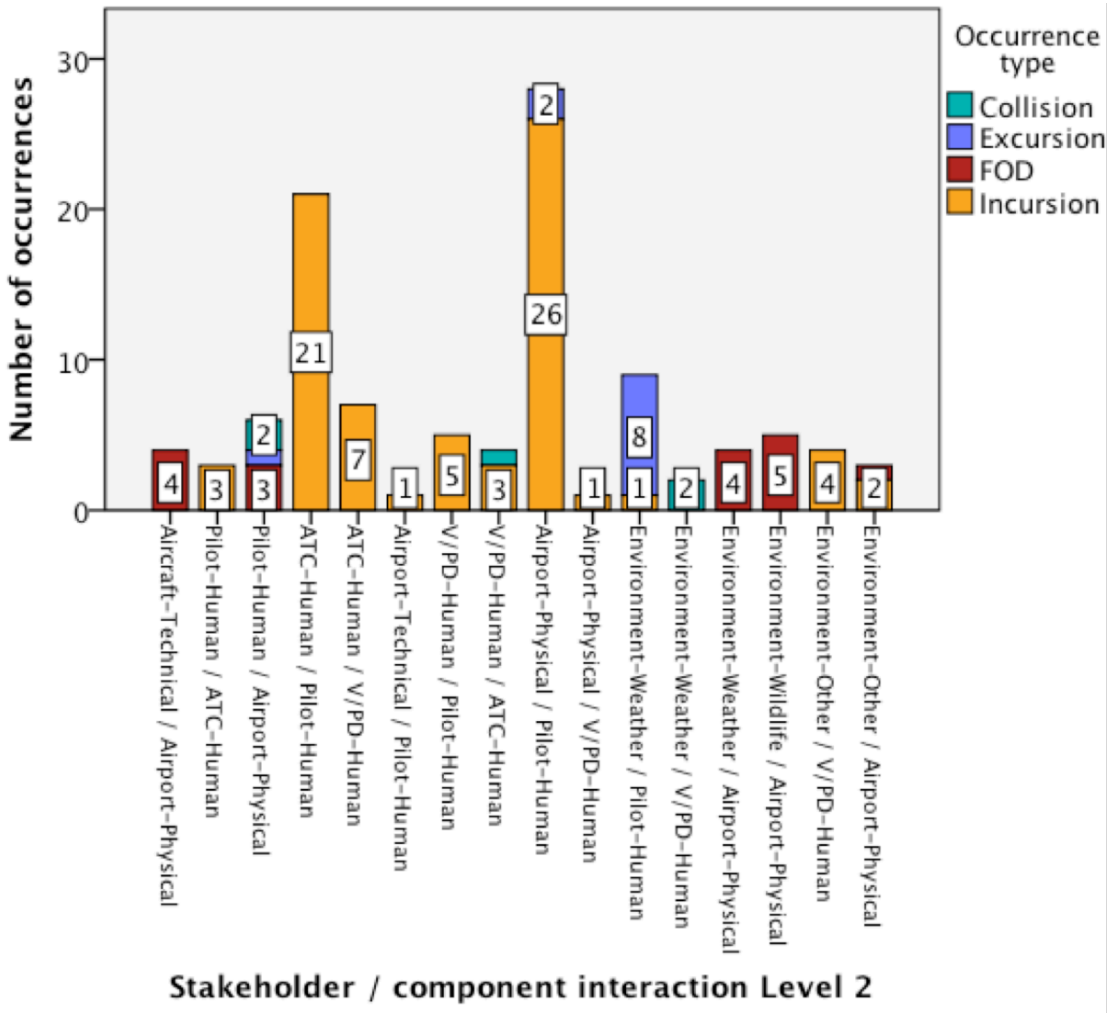


Figure 90: Factor combinations (Level 2) NO

With respect to Norway's wildlife strike data, Table 41 shows the type of animals involved in the reported occurrences for each database. As is the case in the other countries, it was generally not possible to extract a causal factor from most wildlife occurrence reports. The Avinor-Airports data, however, did allow the identification of the causes of wildlife strikes in ten cases. The causes identified were:

- Animals coming through a hole under the fence;
- Animals coming through a hole in the fence;
- Animals jumping over the fence;
- Person feeding birds; and
- Fishing industry next to the airport attracts birds.

Table 41: Wildlife occurrences NO

Animal	Organisation					Total
	Avinor-Airports	Avinor-ANSP	CAA-Norway	Norwegian	OSL	
Bird	441	148	3	296	17	878
Cat	1	-	1	-	-	2
Cow	1	-	1	-	-	2
Deer	26	4	18	-	-	48
Dog	-	1	3	-	2	6
Elk	-	-	8	-	-	8
Fox	10	5	19	-	-	34
Lamb	3	-	3	-	-	6
Moose	16	3	8	-	-	27
Otter	1	-	-	-	-	1
Rabbit	7	2	-	-	-	18
Sheep	5	-	6	-	-	11
Unknown	-	-	29	-	-	29
Total	511	163	108	296	19	1070

The ANSP collected the highest number of wildlife strikes and, therefore, its data for 21 airports was used to analyse relationships with airport location and surrounding land use. Table 42 shows the Point-Biseial Correlation Coefficients (r_{pb}).

Table 42: Correlation coefficients wildlife strike analysis NO

Variable	Norway n = 21
Presence of sea	r_{pb} = -.219; Sig. (2-tailed) .340; r_{pb} = -.219; Sig. (1-tailed) .170
Presence of lake	Variable is a constant
Presence of river	r_{pb} = .036; Sig. (2-tailed) .877; r_{pb} = .036; Sig. (1-tailed) .439
Presence of forest	Variable is a constant
Presence of mountains	No data available*
Presence of field	r_{pb} = -.158; Sig. (2-tailed) .494; r_{pb} = -.158; Sig. (1-tailed) .247
Presence of residential area	r_{pb} = -.159; Sig. (2-tailed) .492; r_{pb} = -.159; Sig. (1-tailed) .246

* The images from Google Earth were not clear enough to extract reliable data.

Similarly to the U.S. Northeast, no correlations were identified between the land use surrounding the airport and the normalised number of reported wildlife strikes in Norway.

7.4.4 Comparison of Stakeholder Viewpoints

After having analysed each database for causal factors, the reports of the different databases were matched to see whether the stakeholders capture accidents / incidents from different perspectives. To match the occurrence reports from the various databases each database was ordered chronologically. Data from 2008 to 2010 was considered for this analysis and wildlife data excluded. Subsequently, the reports were matched based on the occurrence date, time and location (i.e. airport). In case several occurrences happened on the same day at the same airport, the descriptive narratives were read in order to make sure that reports referring to the same occurrence were matched.

The results of the analysis were validated with senior safety investigators from Avinor ANSP in face-to-face interviews (Structured communication with Safety Investigatiors Avinor AS ANSP, June 2011). The results were presented and the SMEs were asked to comment on their validity.

- **Distribution of reports across stakeholders**

A total of 990 airport surface safety occurrences were identified over the time period considered. Figure 91 shows the number of parties that reported these accidents / incidents in overview and Table 43 shows the distribution of reports per stakeholder.

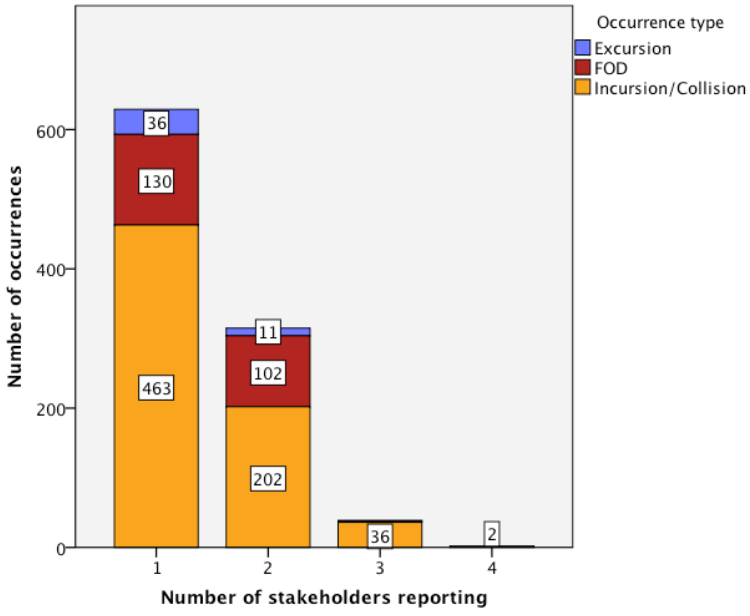


Figure 91: Number of stakeholders reporting NO

Table 43: Distribution of reports per stakeholder NO

Stakeholder / combination of stakeholders who reported	Percentage of occurrences reported by only one stakeholder	Percentage of occurrences reported by two stakeholders	Percentage of occurrences reported by three stakeholders	Percentage of occurrences reported by four stakeholders
CAA_Norway	29.2%			
Avinor-ANSP	29.4%			
OSL	21.2%			
Avinor-Airports	16.7%			
Norwegian	1.9%			
Wideroe	1.6%			
Total	100.0%			
CAA-Norway / Avinor-ANSP		42.9%		
CAA-Norway / Avinor-Airports		41.9%		
Avinor-ANSP / OSL		5.7%		
CAA-Norway / OSL		4.4%		
Avinor-ANSP / Avinor-Airports		1.3%		
Avinor-ANSP / Wideroe		1.3%		
CAA-Norway / Wideroe		1.0%		
CAA-Norway / Norwegian		0.6%		
Avinor-ANSP / Norwegian		0.6%		
OSL / Wideroe		0.3%		
Total		100.0%		
CAA-Norway / Avinor-ANSP / OSL			77.0%	
CAA-Norway / Avinor-ANSP / Avinor-Airports			7.7%	
CAA-Norway / Avinor-ANSP / Norwegian			5.1%	
CAA-Norway / Avinor ANSP / Wideroe			5.1%	
Avinor-ANSP / OSL / Norwegian			5.1%	
Total			100.0%	
CAA-Norway / Avinor-ANSP / OSL / Norwegian				100.0%

The analysis in Figure 91 and Table 43 shows that the majority of occurrences (i.e. 64.0%) were only captured by a single stakeholder. CAA reports that have no matching entries in another database are most probably occurrences reported by other airlines (i.e. not Norwegian or Wideroe). A total of 220 occurrences were found only in either the Avinor-ANSP or Avinor-Airports databases. However, the validation of the results with SMEs revealed that this is incorrect. The SMEs pointed out that both Avinor-ANSP and Avinor-Airports have an automated reporting process to the CAA-Norway. That is, as soon as a report is received a copy is sent to the regulator and, therefore, each occurrence captured in the Avinor-ASNP and Airports data should have a matching entry in the regulatory database.

To verify the results the analysis was repeated as described above, and the initial results were confirmed. In addition, the regulatory data was searched for reports that were only found in the Avinor-ANSP and Airports databases (i.e. by date, descriptive narrative, and key words such as aircraft call sign). However, no matching reports could be identified.

For this research Avinor-ANSP and Airports' entire databases were available and the relevant occurrences were extracted manually. On the other hand, the CAA-Norway provided only data for requested occurrence types (i.e. runway incursions, taxiway incursions, ground collisions, excursions, FOD, wildlife strikes, bird strikes). Assuming that all ANSP and Airport reports go to the regulator, a possible explanation for the loss of information could be found in the occurrence classification. For example, incursions identified only in the Avinor-ANSP and Airports databases showed various classifications (e.g. aircraft deviated from the cleared route; NULL – i.e. no classification assigned; aircraft, vehicle, people or animals moving on the runway without clearance; unauthorised traffic on the manoeuvring area, etc.). Manual sorting allowed for the identification of these occurrences relevant to the context of surface safety. Accidents / incidents identified as relevant in the ANSP and Airports data might, however, not be classified as runway / taxiway occurrences in the regulatory database and, therefore, might not have been captured during the data query. The problem of inadequate / misleading occurrence classifications has already been raised during the data pre-processing in Chapter 6.

This loss of information in the system has implications, since analyses on a national level might be based on incomplete data. Chapter 4 highlighted that it is the State's responsibility to define an acceptable level of safety (ALoS) and to set safety targets at the national level. The current analysis, however, showed that the data used for such

assessments could be insufficient. Chapter 5 noted that the quality of reports varies depending on the quality of the reporting system that is used by the stakeholders. In addition, the current analysis showed that some of the stakeholders in Norway do not report all occurrences to the regulator. The percentages of occurrences reported to the CAA by the primary stakeholders vary. Furthermore, the analysis indicated that there is a problem in the system that leads to the loss of a large amount of information. Therefore, national data can vary on three different levels: occurrence report, primary stakeholder and regulator. The use of such data to define an ALoS is therefore questionable.

If combined with safety data from other countries that may have a different safety / reporting culture, a fourth factor that challenges the equality of safety data is introduced. This has implications for multi-national reporting systems such as ECCAIRS. On a European level such data is used for safety reviews and to monitor the safety of the aviation system. Based on the findings of this research, the effectiveness of such practices must be questioned.

The analysis of the Norwegian data also indicated that there is underreporting in some of the databases. For instance, one report of an occurrence whereby an aircraft committed a taxi error at a certain intersection in one of the airport operator's databases stated: "I will in general admit that I do not always report a taxi error on taxiway S vs. T. This taxi error happens quite often and it happens that this incident is forgotten / downplayed."

- **Causal factors captured by stakeholders**

In the next step, the reports that were captured by only a single stakeholder were analysed further. The occurrences were analysed for their causes in order to see into which stakeholder's responsibility the extracted causal factors fall. Table 44 shows the factors in overview.

Table 44 shows that all of the stakeholders do keep data that falls into the responsibility of other parties. For example, 18.8% of all occurrences were only found in the database of the Norwegian ANSP. Of the extracted causal factors only 10.0% refer to ATC-related failures and, therefore, 90.0% of causes fall into the responsibility of another stakeholder. The results highlight that the stakeholders would benefit from sharing aviation safety data.

Table 44: Causal factors (Level 1) per stakeholder NO

Stakeholder	Aircraft operations	ATC	Airport operations	Environment
Regulator (CAA-Norway)	43.6%	7.2%	45.6%	3.6%
ANSP (Avinor)	55.0%	10.0%	34.6%	0.4%
Airport (Avinor)	82.0%	4.5%	11.2%	2.3%
Airport (OSL)	32.5%	7.3%	58.6%	1.6%
Airline (Norwegian)	74.1%	14.8%	11.1%	0.0%
Airline (Wideroe)	89.7%	10.3%	0.0%	0.0%

- **Reporting structure**

After analysing the occurrences only captured by one party, the following section analyses the accidents / incidents captured by multiple parties. A total of 356 occurrences (i.e. 36.0% of the total data) were reported by at least two stakeholders.

In fact, 95.5% of those reports were identical, i.e. written by one stakeholder and forwarded to another one who just kept a copy. Different reports were identified for just 4.5% of occurrences. Of these, 1.4% came to the same conclusions. However, in 3.1% of cases the reports were complementary and by combining them it was possible to gain a more detailed understanding of why the occurrence happened. This indicates once again that multiple reports have the potential to be beneficial, and conforms to the findings from the analysis of the UK data. Figure 92 summarises the reporting structure in Norway as derived from the data and validated through SMEs.

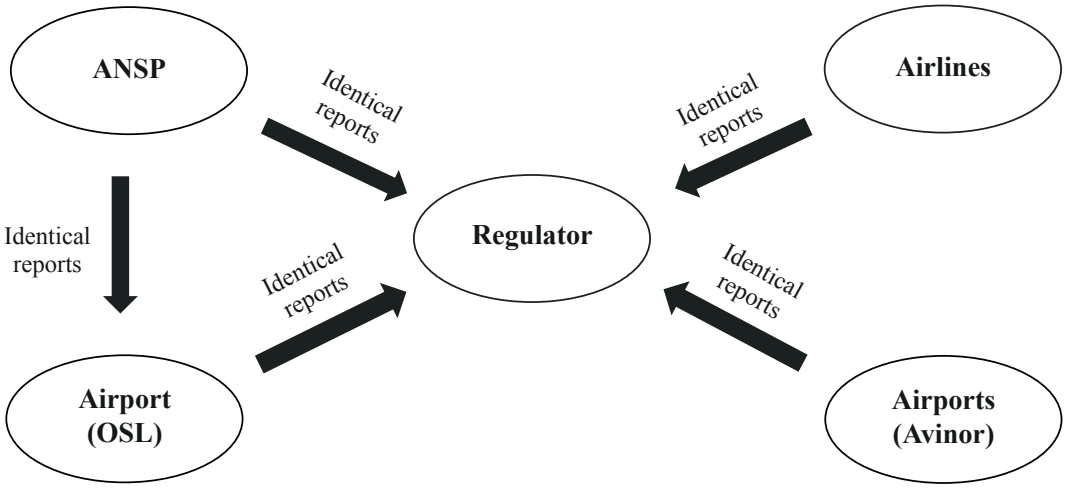


Figure 92: National reporting system NO

The airports, ATC and airlines report to the CAA-Norway and the regulator keeps a copy of the original reports in their database. However, the investigation findings that are added later to the reports in the primary databases are not passed on to the regulator. In addition, the ANSP forwards a copy of their reports to the airport operator OSL who keeps these copies in its database. If the same occurrence is reported by an airline and ATC the reports differ. Similarly, the airlines and airports each write their own reports for accidents / incidents, and also, the reports between ANSP and Avinor-Airports differ. Hence, in order to capture multiple perspectives each occurrence should ideally be captured by the airports, airlines and ATC. The regulator on the other hand aggregates this information only for monitoring purposes.

7.4.5 Examination of Relationships

In the final part of the analysis the data was tested for associations between the variables. As the number of collisions was too low to be used for statistical analysis, these accidents were aggregated with the incursion data. In addition, the wildlife data was excluded in order to make the analysis comparable to the U.S. and UK.

The analysis showed a significant association between the type of stakeholder and the occurrence types X^2 (6) = 235.125, p < .001. Cramer's V = .290, p < .001 indicates a moderately strong relationship (Figure 93).

There was also a significant association between the type of stakeholder and the causal factors on the first level of the taxonomy X^2 (9) = 304.026, p < .001. With a value of .213, p < .001 Cramer's V indicates a moderately strong relationship (Figure 94).

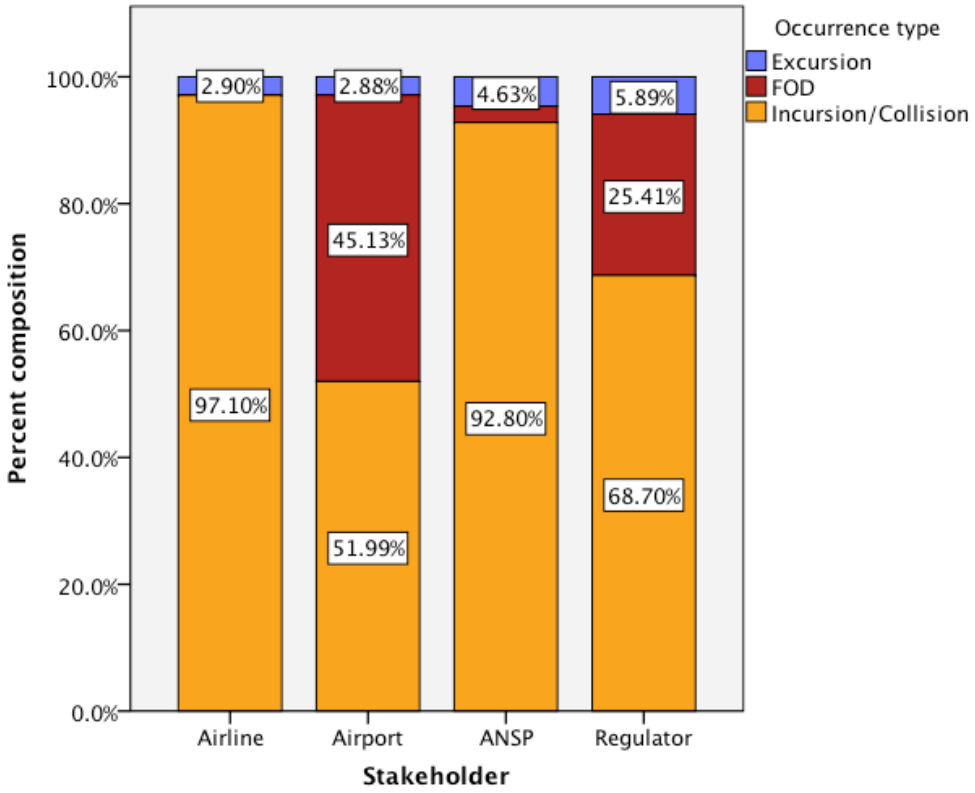


Figure 93: Occurrence type per stakeholder NO

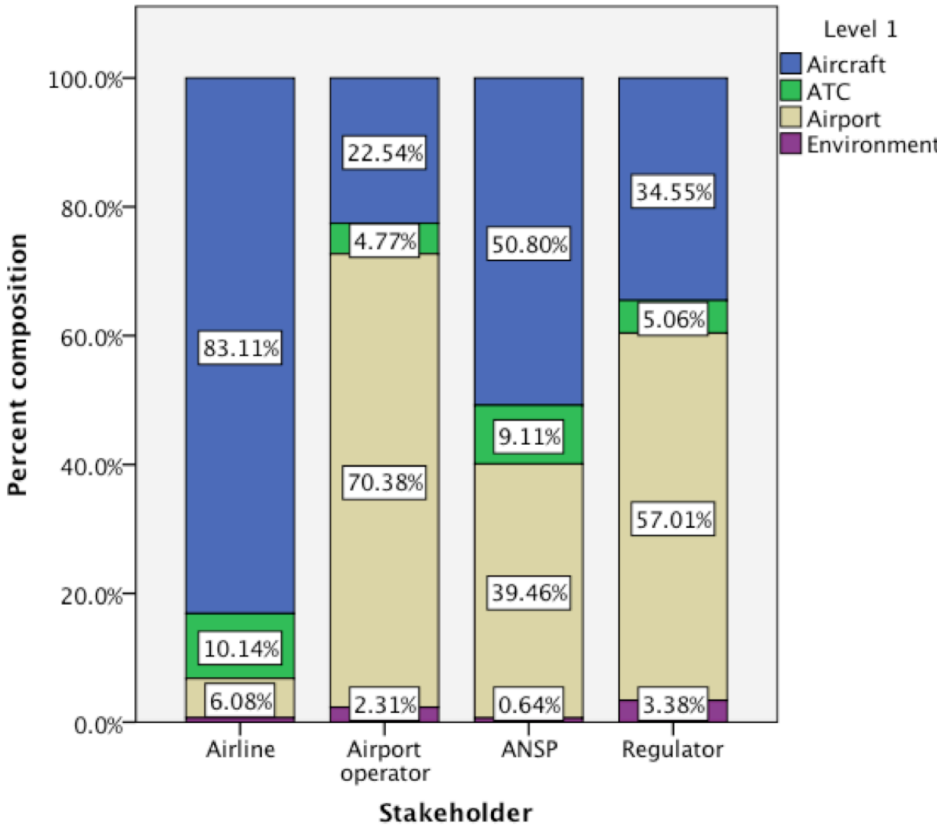


Figure 94: Causal factors (Level 1) per stakeholder NO

Subsequently, the data was tested for associations between occurrence types and causal factors (Level 1) with the analysis revealing a significant association between the two variables (Level 1) X^2 (6) = 491.029, p < .001. Cramer's V indicates a strong relationship with a value of .331, p < .001 (Figure 95).

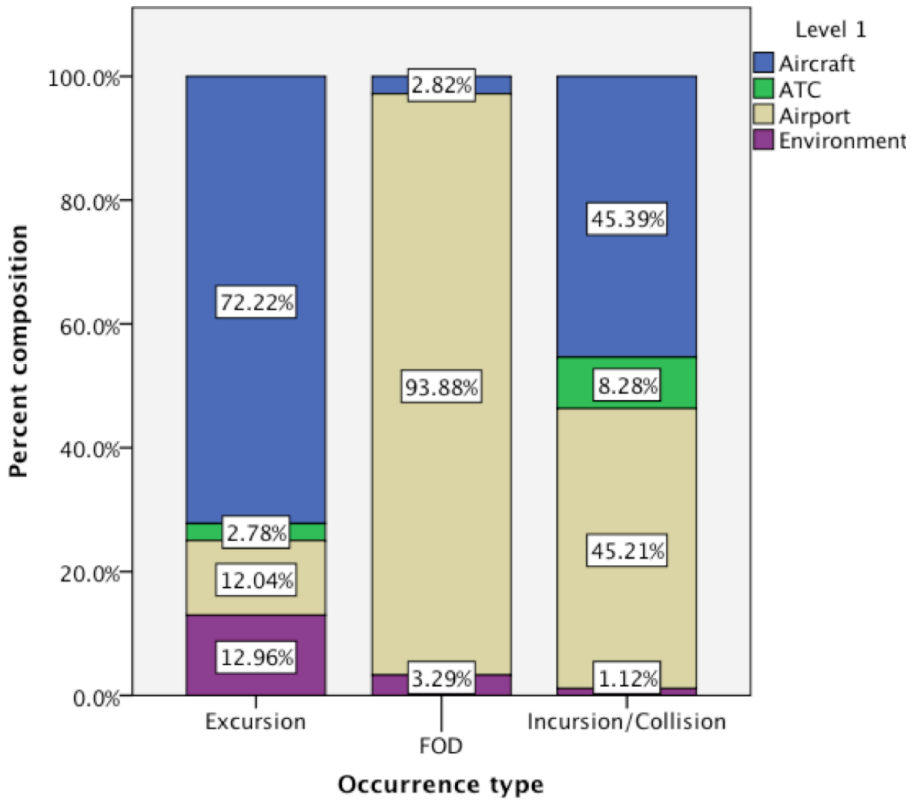


Figure 95: Causal factors (Level 1) per occurrence type NO

In addition to testing the data on an aggregated level, the relationship between the occurrence types and the causal factors was tested for each database individually. Table 45 contains the results. An analysis for the Wideroe data was not possible because the Sentinel data contained only incursions.

Table 45: Causal factors (Level 1) per occurrence type per stakeholder NO

Database	**Test statistics Chi-Square test**		
	X^2	**Sign.**	**Test assumptions**
CAA-Norway ECCAIRS	195.948	P < .001	Violated
Avinor-ANSP MESYS	35.441	P < ..001	Violated
Avinor-Airports MESYS	131.677	P < ..001	Violated
OSLIFS	42.697	P < ..001	Violated
Norwegian AQD	6.144	P > .05	Violated

Table 45 shows that all test statistics violated the assumptions of the Chi-Square test, and that the data samples from the individual organisations are not large enough for statistical analysis.

A further analysis considered whether an association exists between airports and the causal factors. To test this relationship the example of the Avinor-ANSP MESY database was used since this database refers to only a small number of airports (21 airports). The results show a significant association X^2 (60) = 164.783, p. < 001. However, the test assumptions are violated with 60.7% of cells having an expected count of less than five. Also, when excluding the lowest populated category of causal factors (i.e. environment) the results improved only marginally (X^2 (40) = 134.877, p < .001; 47.6% of cells having an expected count of less than five). Therefore, the results are invalid, and more data is needed for statistically rigorous analysis.

7.4.6 Conclusions Norway

The following conclusions can be drawn from the analysis of the Norwegian data:

- An active promotion of a safety culture can influence the number of reports;
- The normalised number of reported occurrences is higher at small regional airports;
- An analysis of new data sets can bring so far unknown causal factors to light;
- The analysis indicated that not all causal factors are relevant for all parties, and that the stakeholders' operations (i.e. tasks) influence the factors that are reflected in the databases;
- National variations for the causal factors were identified and possible reasons discussed;
- There are statistical associations between stakeholders and occurrence types, stakeholders and causal factors, and occurrence types and causal factors.
- The quality of safety data varies on four levels: i) the individual report, ii) the reporting system of the primary stakeholder, iii) the regulatory reporting system, and iv) the national safety / reporting culture.

7.5 New Zealand

7.5.1 Data Overview

The ASMS database provided by the regulatory body of New Zealand, the NZ CAA, was assessed. A total of 220 occurrences were analysed over a period of ten years and Table 46 shows the data in overview.

Table 46: Data overview occurrences NZ

Stakeholder / database	Geographical location		Number of occurrences					Number of airports involved	Considered time period
		COL	IN	EX	FOD	WL	Total		
Regulator / ASMS	NZ	9	148	62	1	0	220	60	2000 - 2009

7.5.2 Occurrence Rates

There is no regulatory requirement for airports to report their movements in New Zealand and, consequently, normalisation data was only available for 20 of the 60 airports. The airports without data are mainly small regional airfields that accounted for 25.5% of all occurrences. Missing data means it is not sensible to show the trend of occurrences, as this might be misleading.

7.5.3 Frequency Analysis

A total of 484 causal factors were extracted from the data (Table 47) and their distribution at the first and second taxonomy level are shown in Figures 96 and 97.

Table 47: Data overview causal factors NZ

Stakeholder	Database	Number of occurrences	Number of critical factors extracted	Number of different critical factors extracted from the database
NZ CAA	ASMS	220	484	169

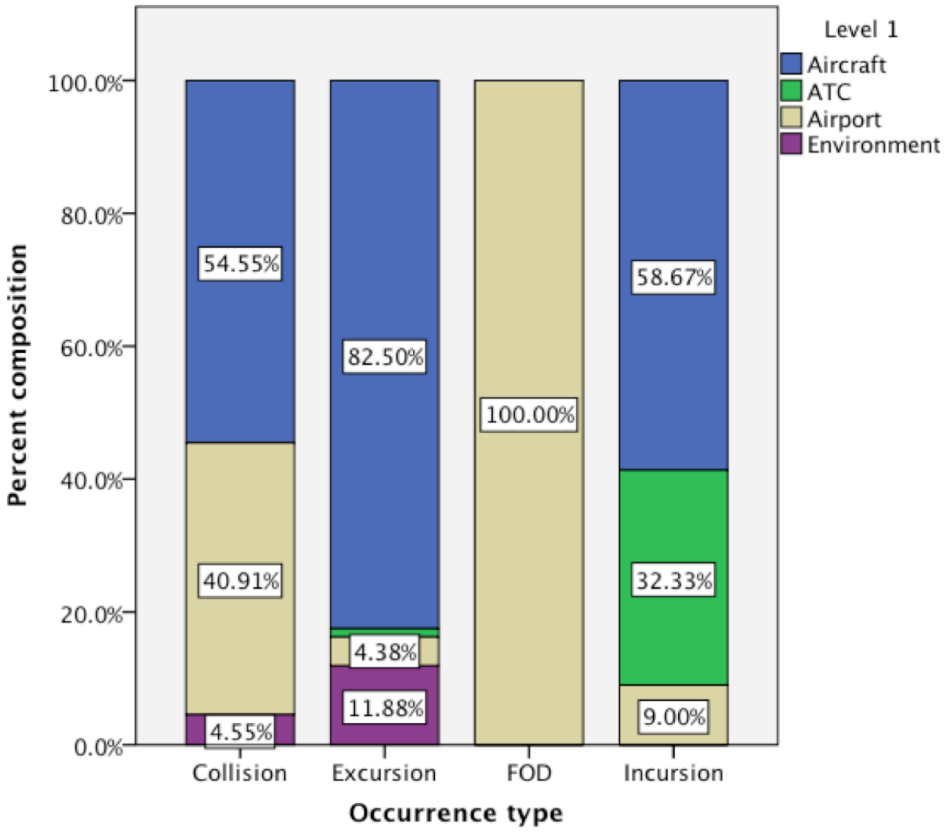


Figure 96: Causal factors (Level 1) per occurrence type NZ

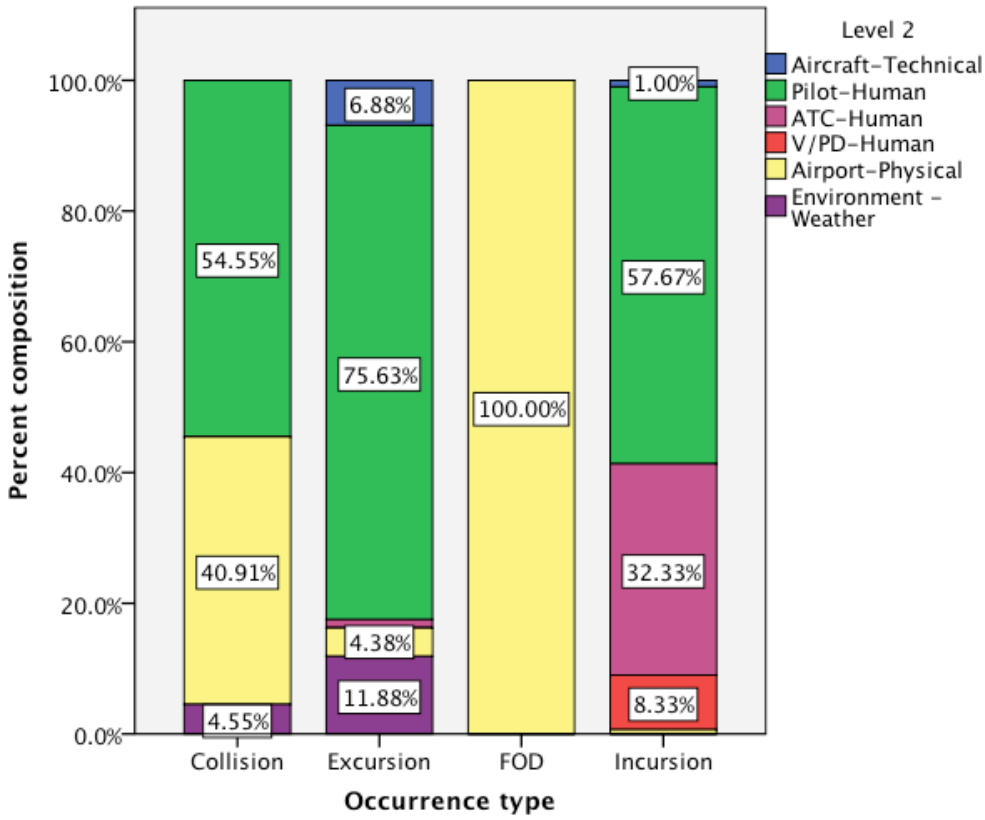


Figure 97: Causal factors (Level 2) per occurrence type NZ

The majority of reported occurrences are incursions and excursions. At a high level, the NZ CAA captures similar factors as seen in the other countries. Aircraft technical failures, pilot-related factors, airport physical characteristics and weather are reported causes of excursions. Incursions are caused predominantly by human-related factors (i.e. pilot, ATC, V/PD).

Although, at a high level, the causal factors are similar to those reported in other countries, they vary in terms of their frequency and detail. This becomes apparent when analysing the data at the level of factors. The NZ CAA captures a large variety of factors with a total of 169 different causal factors. In comparison to the other countries, ATC technical factors, airport technical factors, and factors in relation to the regulatory system are not captured in New Zealand's ASMS database.

The causal factors most frequently extracted from the occurrence reports are shown in Table 48. The quantities indicate the percentage of occurrences that had a particular factor underlying them. The top causal factor contributing to 15.5% of accidents / incidents relates to ATC issuing conflicting clearances. Unlike the other countries, ATC has an important role at New Zealand's airports.

Table 48: Top 10 causal factors NZ

Stakeholder	Database	Top 10 causal factors
NZ CAA	ASMS	1. ATC issuing conflicting clearances (15.5%); Pilot entering runway without authorisation (15.5%); 3. Loss of control over the aircraft while on the runway (12.3%); 4. Pilot took off without clearance (8.2%); 5. Pilot landed or departed on the wrong / closed runway (5.5%); Pilot not stopping at the required position in front of a runway (hold line) (5.5%); 7. ATC mishandling of flight strips (5.0%); Pilot entering taxiway without authorisation (5.0%); 9. Wind shear, gusts, other winds (4.6%); 10. Pilot inexperience / student pilot (4.1%); Pilot correct read back, followed by an unauthorised manoeuvre (4.1%); Short landing (4.1%)

For 91 occurrences, i.e. 41.4% of the total number, it was possible to extract two causal factors from the occurrence reports. As seen before, only the minority of occurrences (19.8%) showed an interaction between stakeholders and / or components of the airport surface system. Similar to Norway, interactions between pilots and airport physical

characteristics occurred most frequently (six times). In addition, the influence of weather on pilot performance caused six of the accidents / incidents.

7.5.4 Examination of Relationships

Finally, the data was analysed for associations between occurrence types and causal factors (Figure 98). As collisions are rare they were aggregated with incursions. Additionally, the single FOD occurrence was excluded from the analysis.

There was a significant association between the occurrence type and the causal factors at the first taxonomy level X^2 (4) = 93.011, p < .001. Cramer's V indicates an extremely good relationship (4.39, p < .001).

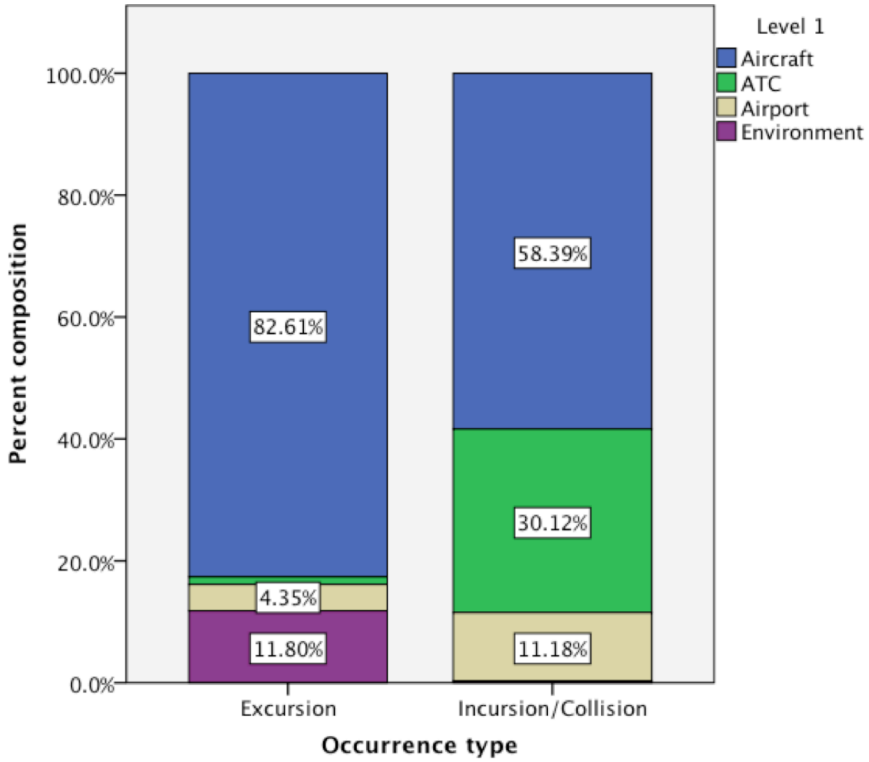


Figure 98: Causal factors (Level 1) per occurrence type NZ

In addition, the relationship between airports and causal factors was tested. Again, the occurrence categories of incursions and collisions were combined and the FOD occurrence excluded from the analysis. There was a significant association between airports and causal factors (X^2 (87) = 144.214, p < .001). However, with 85.0% of cells having an expected count less than 5 the test assumptions are violated invalidating the results.

7.5.5 Wildlife Analysis

To understand the causes of wildlife strikes better the data was correlated to characteristics of the airport location and airport surrounding land use. Section 6.6.12 discussed that New Zealand's database contains two spread-sheets (i.e. with investigation findings, without investigation). The wildlife strike data was extracted from the spread-sheet without investigation findings. The analysis was limited to the 20 airports for which normalisation data was available. All wildlife strike data has been normalised using the number of movements per airport per year.

Table 49 shows the Point-Biseial Correlation Coefficients (r_{pb}).

Table 49: Correlation coefficients wildlife strike analysis NZ

Variable	**New Zealand n = 20**
Presence of sea	r_{pb} = -.001; Sig. (2-tailed) .998; r_{pb} = -.001; Sig. (1-tailed) .499
Presence of lake	r_{pb} = -.275; Sig. (2-tailed) .174; r_{pb} = -.275; Sig. (1-tailed) .087
Presence of river	r_{pb} = -.103; Sig. (2-tailed) .617; r_{pb} = -.103; Sig. (1-tailed) .308
Presence of forest	r_{pb} = .035; Sig. (2-tailed) .865; r_{pb} = .035; Sig. (1-tailed) .432
Presence of mountains	r_{pb} = -.107; Sig. (2-tailed) .603; r_{pb} = -.107; Sig. (1-tailed) .302
Presence of field	r_{pb} = -.178; Sig. (2-tailed) .386; r_{pb} = -.178; Sig. (1-tailed) .193
Presence of residential area	r_{pb} = -.185; Sig. (2-tailed) .365 r_{pb} = -.185; Sig. (1-tailed) .183

No correlations were identified between the land use surrounding the airport and the normalised number of reported wildlife strikes and possible reasons were discussed in section 7.2.7.

7.5.6 Conclusions New Zealand

The analysis of the data gathered from New Zealand confirmed the findings from the other countries and similar causal factors were identified to those seen previously. However, the factors varied in frequency and detail. Furthermore, an association between

occurrence types and causal factors was found. As only regulatory data was available for New Zealand, the impact of the stakeholders on occurrences and causal factors could not be analysed.

7.6 Discussion

This section concludes the analysis of causal factors at the State-level and summarises the findings concerning occurrence rates, causal factors, reporting and data quality, and analytical methodologies. The main results of the analysis of causal factors are summarised in Table 50, which shows the percentage of occurrence types and causal factors per organisation.

The rates of reported occurrences differ considerable between the databases and the various reasons for this have been discussed throughout this chapter. Apart from data quality issues, this chapter has identified other strong reasons as to why occurrence rates differ (e.g. operating procedures, active safety promotion) across organisations and, therefore, why such data cannot be compared. In most countries it was the smaller airports that showed the highest number of reported occurrences (per 100,000 movements).

The analysis showed that the various stakeholders capture different occurrence types and underlying causal factors in their databases. Significant associations between the type of stakeholder and the occurrence type, as well as the type of stakeholder and the causal factors were found. In addition, the data showed variations in the distribution of the causal factors as captured through the stakeholders, i.e. the stakeholders capture the causal factors in different frequencies. The analysis further identified situations in which the stakeholders capture causal factors that fall into the responsibility of another actor. In addition, situations were found in which a stakeholder failed to capture factors that are critical for their own operations. This points to an inadequacy in their system, either through not realising that there was a problem, or inadequate reporting practices. In both cases, data sharing would be beneficial.

A minority of occurrence reports captured interactions between different causal factor groups. This proves, however, that occurrences can be caused by an interaction between stakeholders and / or other system components and that safety risk assessments must address all components of a system and their interactions.

Table 50: Summary causal factor analysis

	RI Database (ANSP)	**AIDS (Regulator)**	**SHEBBA (Ground handling)**	**MORS (Regulator)**	**easyJet AQD (Airline)**	**ECCAIRS (Regulator)**	**MESYS (ANSP)**	**MESYS (Airport operator)**	**IFS (Airport operator)**	**Norwegian AQD (Airline)**	**Sentinel (Airline)**	**ASMS (regulator**
Occurrence Type												
Incursions / collisions	✓✓✓✓		✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Excursions		✓✓✓✓	✓✓✓	✓✓✓	✓	✓✓	✓	✓	✓	✓		✓✓✓
FOD		✓✓		✓✓	✓✓✓✓	✓✓✓	✓	✓✓✓✓	✓✓			✓
Taxonomy Level 1 and 2												
Aircraft operations												
Aircraft - Technical	✓	✓✓✓		✓✓		✓	✓	✓	✓	✓		✓
Pilot - Human	✓✓✓✓	✓✓✓	✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
ATC												
ATC Technical	✓			✓	✓		✓	✓				
ATC – Human	✓✓	✓		✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓	✓✓	✓✓
Airport operations												
Airport - Technical	✓			✓	✓	✓	✓	✓	✓			
V/PD – Human	✓✓		✓✓✓✓	✓✓	✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓		✓✓
Airport Physical	✓	✓✓	✓✓✓	✓✓	✓✓✓	✓✓	✓✓	✓✓✓	✓✓	✓		✓
Environment												
Weather	✓	✓✓	✓	✓✓	✓	✓	✓	✓	✓	✓		✓
Other	✓	✓	✓	✓		✓		✓				
Regulatory system												
Top 3 Taxonomy Level 3	1. Pilot – Human reliability 2. V/PD – Human reliability 3. Pilot – Communi-cations	1. Pilot – Human reliability 2. Aircraft – technical failure 3. Winds	1. V/PD – Human reliability 2. RWY / TWY conditions 3. Weather	1. Pilot – Human reliability 2. V/PD – Human reliability 3. Pilot – Communi-cations	1. RWY / TWY conditions 2. Pilot – Human reliability 3. Pilot situational awareness	1. Pilot – Human reliability 2. V/PD – Human reliability 3. RWY / TWY conditions	1. Pilot – Human reliability 2. V/PD – Human reliability 3. Pilot – Communi-cations	1. RWY / TWY conditions 2. V/PD – Human reliability 3. Aerodrome operations	1. Pilot – Human reliability 2. V/PD – Human reliability 3. RWY / TWY conditions	1. Pilot – Human reliability 2. Pilot situational awareness 3. Pilot resources	1. Pilot – Human reliability 2. Pilot – Communi-cations 3. ATC communi-cations	1. Pilot – Human reliability 2. ATC human reliability 3. Pilot situational awareness

Note: wildlife strikes have been excluded from this analysis.
✓: Causal factors accounted for less than 5.0% of all causal factors, ✓✓: Causal factors accounted for 5.01% to 25.0 % of all causal factors, ✓✓✓: Causal factors accounted for 25.01 % to 50.0% of all causal factors, ✓✓✓✓: Causal factors accounted for more than 50.0% of all causal factors

Where it was possible to compare the occurrence reports from different stakeholders they were often found to be complementary. In particular, airline data provided additional information as to why occurrences happened which was not captured in e.g. ATC or regulatory databases. Therefore, 'real multi-reporting', i.e. the reporting of an occurrence by several stakeholders, seems beneficial.

The hybrid methodology (i.e. safety data, interviews, observations, statistical analysis) that has been employed in this chapter enabled a detailed understanding of the causal factors. Indeed, interviews and observations provided additional information to the analysis of safety data and revealed further national differences between the stakeholders.

Concerning the quality of the safety data, it was found that this can vary on four levels: i) the individual report, ii) the reporting system of the primary stakeholder, iii) the regulatory reporting system, and iv) the national safety / reporting culture. The implications of this for e.g. the definition of ALoS at the State-level and multi-national reporting systems were discussed. In addition, the analysis also indicated that some databases are underreported.

7.7 Summary

This chapter has analysed the causal factors of airport surface accidents and incidents captured in twelve safety databases. To enhance the understanding of certain fuzzy areas the analysis was complemented by interviews and observations, and statistical analysis. By using this hybrid methodology a holistic understanding of the causes for airport surface safety occurrences was achieved. With this, the analysis contributed to the fifth research objective and closed major gaps in the literature.

Whilst this chapter analysed the causal factors at the State-level, the next moves on to analysing the factors at the cross-State level.

8 Cross-State Analysis

The previous chapter has introduced a methodology to analyse the causal factors of airport surface safety occurrences and applied it at the State-level. This chapter applies the methodology in part to the cross-State level. It explores the differences in the causal factors and their drivers across stakeholders in order to understand the unique contribution of each of the stakeholder to the safety of surface operations. In addition, this chapter analyses the relationships between the different occurrences types and their common causes. The results of the data analysis are used to update the airport surface system architecture and to refine the initial process model developed in Chapter 3.

8.1 Cross-Stakeholder Comparison

The previous chapter compared the causal factors across stakeholders for each of the countries individually. This section aims to highlight the differences between stakeholders at the cross-State level. To do so, the twelve databases are aggregated per stakeholder type and Table 51 shows the stakeholders in overview.

Most reports that are captured in the RI database are received by ATC (Structured communication with FAA Runway Safety Office Analysts, August 2011). It is for this reason that the RI database was classified as reflecting the ANSP perspective. The FAA AIDS database, on the other hand, is a compilation of accident and serious incident reports populated primarily from National Transportation Safety Board (NTSB) reports. The NTSB is an independent federal agency responsible for investigating civil aviation

accidents in the U.S. (Federal Aviation Administration, 2013a). These reports therefore, represent the regulatory perspective.

Table 51: Stakeholder overview

Database	Stakeholder perspective
FAA AIDS	Regulator
UK CAA MORS	
CAA - Norway ECCAIRS	
NZ CAA ASMS	
FAA RI Database	ANSP
Avinor – ANSP MESYS	
Avinor – Airports MESYS	Airport operator
OSL IFS	
easyJet AQD	Airline
Norwegian AQD	
Wideroe Sentinel	
Signature SHEBBA	Ground handling company

Comparing the causal factors across stakeholders has four steps. To begin with, the analysis correlates the stakeholders to the relevant parts of the taxonomy. In addition, Chapter 6 analysed the variety of causal factors captured in each of the databases in relation to data quality. That analysis concluded that the normalised number of different causal factors is correlated to the quality of the data (i.e. DQI). To complement that analysis, the data is tested for associations between the normalised number of different causal factors and the type of stakeholder. Subsequently, the contribution of the individual stakeholders is shown and the causal factors that are unique for each stakeholder determined. This is followed by an examination of relationships between occurrence types, causal factors and stakeholders.

8.1.1 Frequency Analysis

The analysis was carried out for each occurrence type separately and Table 52 shows the distribution of causal factors across stakeholders at the second taxonomy level.

For incursions / collisions, the regulatory and ANSP data show a similar distribution of causal factors. Pilot-related factors were collected most frequently, followed by V/PD human-related factors, and ATC human-related factors third. However, the regulators capture a greater variety of factors, including e.g. environmental factors. The reason for this is that the regulatory databases combine reports made by all aviation stakeholders. The

airport operators capture around 47.0% of V/PD human-related factors while the airlines predominantly capture pilot-related factors (75.6%). Ground handling, meanwhile, captures mainly V/PD human-related factors (88.8%).

In contrast to incursions / collisions, the excursion data shows a very different distribution of causal factors across the stakeholders. Regulators capture mainly pilot-related factors and aircraft technical issues, followed by the contribution of weather. The ANSP on the other hand, shows predominantly pilot-related factors and problems associated with airport physical characteristics. In contrast, in the regulatory database, airport physical characteristics accounted for only 5.2% of all causal factors, indicating that risk mitigation strategies developed by different stakeholders based on their own accident / incident data would probably focus on different aspects of surface safety.

Interestingly, the airport operators do not capture problems associated with the physical surface infrastructure. This indicates that the airport operators are either unaware of such problems, or do not report them. The first scenario might cause problems to other stakeholders, since e.g. pilots are reliant on well-maintained surfaces and correct surface condition reports, and ATC are responsible for providing this information.

This is confirmed by the airline data, which shows 16.7% of causal factors related to airport-physical characteristics. Indeed, structured communications with two Norwegian pilots revealed that pilots suffer from airports giving them incorrect information (e.g. surface conditions, breaking coefficient) (Structured communication with Norwegian pilots, 2012). There are three possible reasons for this: i) the airports fail to realise that there is a problem, ii) the airports do realise the problem, but fail to act upon it, iii) the airports do realise the problem and take action, but fail to report it. The implications of these scenarios are, in the first case, that the airports would benefit from the safety data kept by the other stakeholders. In the second case, there would clearly be a safety-challenging situation, while the third case would suggest inadequacies in the reporting system.

The FOD data also shows very different distributions of causal factors across the stakeholders. Only in one aspect do the databases conform: that is they all show airport physical characteristics as being the most frequently extracted category of causal factors. The greatest variety of causal factors is captured by the regulators and airport operators. Overall, the analysis highlights that the various stakeholders have a different scope of data collection and therefore capture different causal factors.

Table 52: Causal factors (Level 2) per stakeholder per occurrence type

Causal factors (Level 2)	Regulator	ANSP	Airport operator	Airline	Ground handling company
Incursions / collisions					
Aircraft - Technical	2.8%	0.6%	0.3%	-	-
Pilot – Human	59.2%	66.3%	32.5%	75.6%	1.9%
ATC – Technical	0.1%	0.1%	-	0.4%	-
ATC – Human	9.3%	8.8%	8.1%	9.3%	-
Airport - Technical	0.6%	0.3%	1.0%	0.4%	-
V/PD - Human	21.0%	22.8%	47.0%	7.1%	88.8%
Airport - Physical	2.7%	0.9%	10.6%	6.2%	7.5%
Environment – Weather	3.8%	0.2%	0.5%	1.0%	0.9%
Environment – Geological disturbances	0.1%	-	-	-	-
Environment - Wildlife	-	-	-	-	0.9%
Environment – Other	0.3%	-	-	-	-
Regulations - Inadequate	0.1%	-	-	-	-
Total	100.0%	100.0%	100.0%	100.0%	100.0%
Excursions					
Aircraft - Technical	22.6%	12.5%	15.8%	-	-
Pilot – Human	58.4%	41.7%	63.2%	50.0%	-
ATC – Technical	-	-	-	-	-
ATC – Human	0.3%	-	5.3%	33.3%	-
Airport - Technical	-	-	-	-	-
V/PD - Human	0.1%	4.2%	-	-	-
Airport - Physical	5.2%	33.3%	-	16.7%	-
Environment – Weather	13.3%	8.3%	15.7%	-	-
Environment – Wildlife	0.1%	-	-	-	-
Total	100.0%	100.0%	100.0%	100.0%	-

Causal factors (Level 2)	Regulator	ANSP	Airport operator	Airline	Ground handling company
FOD					
Aircraft - Technical	7.3%	-	1.5%	-	-
Pilot – Human	5.5%	16.6%	2.2%	2.5%	-
ATC – Technical	-	-	-	-	-
ATC – Human	-	-	-	-	-
Airport - Technical	-	-	-	-	-
V/PD - Human	4.8%	41.7%	13.8%	1.3%	4.5%
Airport - Physical	79.1%	41.7%	78.4%	96.2%	86.4%
Environment – Weather	2.9%	-	0.8%	-	9.1%
Environment – Wildlife	-	-	2.9%	-	-
Environment – Other	0.4%	-	0.4%	-	-
Total	100.0%	100.0%	100.0%	100.0%	100.0%

8.1.2 Data Detail

The distribution of the number of different causal factors (as normalised) is the same across categories of stakeholders ($H(4) = 6.14$, p (2-tailed) > .05). This indicates that the detail of the databases is independent of the stakeholder perspective and depends on the quality of the underlying reporting system and hence of the collected data.

8.1.3 Contribution of Individual Stakeholders

The contribution of each of the stakeholders to the understanding of causal factors considered ground handling, airline, airport operator, ANSP and the regulator.

- **Ground handling**

Causal factors found only in the data provided by the ground handing company included factors that were observed by Signature personnel that relate mainly to violations by operators from other companies. These include: V/PD not complying with the traffic rules to give way to preceding traffic; V/PD cutting corners; and V/PD driving too close to other traffic as well as driving too fast. Also, V/PD ignoring the taxiway signs / markings; V/PD overtaking slower vehicles and infringing onto the manoeuvring area; and V/PD driving around a blocked stand and thus entering the manoeuvring area in order to get to their destination were factors identified in the data. Furthermore, vehicles that are parked on the double-yellow lines (i.e. lines that separate the apron from the manoeuvring area) without authorisation were captured as causal factors as well as the unauthorised use of mobile phones.

Often operational personnel report only when they are directly involved in an occurrence, and therefore, such reports are an indication for a very good safety culture within Signature. Other factors identified in Signature's data referred to the incorrect marshalling of aircraft and FOD caused by handling equipment (chocks, marker cones, unit load device (ULD) containers, pallets, tow bars, etc.).

The identified factors relate mainly to V/PD failures and violations which had not been identified in the literature. Also, these factors have not been found in the data from the

airport operators, who also function on the airport surface in form of V/PD. This indicates that the causal factors differ depending on the stakeholder's function. This was confirmed through interviews with ten personnel from two major U.S. airport operators. The interviewees included the Heads of Airfield Operations of both airports, a shift supervisor, an airfield escort for contractors, and six operational personnel and were conducted on an ad-hoc basis. The staff were asked to give the main reasons, from their perspective, why accidents / incidents occur on the airport surface. Their most frequent responses were distraction, situational awareness, complacency, multitasking, personnel problems, fatigue and visibility. None of the interviewees mentioned wilful violations of traffic rules and procedures, as were identified in the ground handling data.

- **Airline**

Causal factors that were only identified in the airlines' data included:

- Inadequate surface infrastructure (e.g. confusing lights; markings partially erased; gaps in taxiway lights) and inadequate documentation (e.g. temporary airport charts are not up to date);
- ATC failures that caused pilot deviations (e.g. ATC used non-English language with other aircraft which led to a loss of situational awareness for the pilot; no taxi routing given by ATC); and
- Pilot factors such as the pilot's incorrect perception of speed or misperception of distances at the airport; pilot expected a different stand and hence a different taxi route; pilot did not check whether the area is clear of other traffic; or pilot announcement to the passengers and coordination with cabin crew.

These factors are more detailed than the ones found in regulatory and ATC databases and shed light on why the accidents / incidents occurred.

- **Airport operator**

The analysis of the airport operators' data revealed factors in relation to the physical airport infrastructure, airport management, security issues and external factors, and V/PD deviations. These included amongst other things snow removal activities; FOD inspection activities; and taxiway management. Likewise, inadequate procedures for maintenance

work and the use of inappropriate materials for maintenance (e.g. use of the wrong kind of lights because the right ones were out of stock) have been reported. Furthermore, the factors: ground handling did not secure the aircraft properly, which started rolling back; V/PD switched off their radio; V/PD did not answer the radio; and drivers that went too far away from the vehicle to be able to hear the radio were reported as having caused occurrences. In one case a V/PD wanting to help another V/PD to get the job done quicker was involved in an incident.

Furthermore, the databases of the airport operators specified FOs on the surface including surface pavement, concrete cracks, and surface infrastructure (e.g. runway edge lights). In addition, the inappropriate use of power / jet blast was reported as cause of FOD. Finally, security issues (e.g. perimeter road not adequately secured; fences snowed under) and the presence of emergency vehicles / ambulances were extracted from the data as causal factors.

- **ANSP**

The ANSP data revealed ATC failures (e.g. ATC misjudgement of timings, which led to a situation that was too tight; ATC did not advise the pilot of a safety challenging situation) and factors that relate to deviations which ATC observed from the control tower. For example, aircraft got disconnected from the tow bar; pilots push back without clearance; pilots simply following another aircraft without clearance; and the wilful non-compliance of pilots with ATC instructions. Furthermore, a controller reported that an aircraft wing infringed onto the runway during an aircraft's turn on a taxiway. The ANSP databases also revealed that Air Traffic Services (ATIS) may not always be up to date. Finally, the limited view of the manoeuvring area through work in progress and the distraction of ATC through visitors in the tower were reported as causes to accidents / incidents.

- **Regulator**

The data collected in regulatory databases added to the understanding of causal factors by revealing, along with general factors, the causes of accidents / incidents that occurred at very small regional airports which are not covered in the databases of the other

stakeholders. These included: unexpected emergency / ambulance flight coming in; landing / departure on a closed airport; and a runway operated at reduced length. Also, a foreign pilot who believed that the same rules apply as in his / her country as well as pilots who were unfamiliar with the ground / tower handover, and underestimated the runway downslope, respectively, were reported. The sudden sink of the aircraft on short final and the controller not being in the tower and doing a break were also factors extracted from the regulatory databases. In addition, vehicle driver and pedestrian factors contributed to occurrences, for instance when a V/PD thought that a 'promise' for the future is automatically a clearance, a V/PD called ATC to ask for clearance, but did not wait for a reply, or a vehicle escort failed to obtain a clearance for a vehicle under his / her responsibility. Finally, a person running out onto the manoeuvring area to take a picture of a landing aircraft was reported to have caused an occurrence.

Overall, most factors depict detailed causes to airport surface accidents and incidents that were not covered in the literature. As shown in the literature review in Chapter 5, the majority of studies on surface safety that are based on safety data use regulatory databases, accident investigation board data, and databases that compile worldwide accidents and serious incidents, but not data from the stakeholders directly involved in surface operations. Therefore, the analysis presented in this thesis allows a unique insight into causal factors from a different perspective.

8.1.4 Examination of Relationships

After showing the distributions of causal factors across stakeholders, this section analyses the data for relationships between the variables. There was a significant association between the type of stakeholder and the occurrence type X^2 (8) = 2999.183, p < .001 (Figure 99). With a value of .498, p < .001 Cramer's V indicates that this association is very strong.

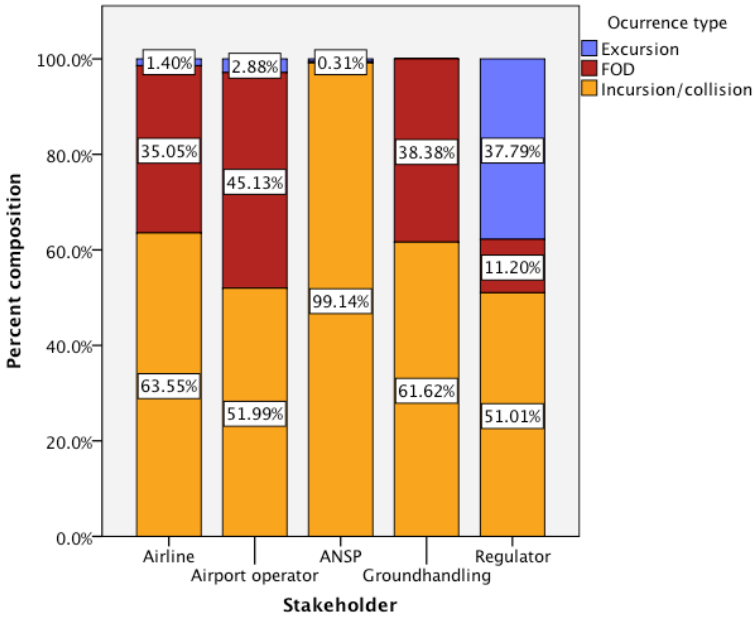


Figure 99: Occurrence type per stakeholder

All stakeholders capture incursions / collisions. In fact, 99.1% of the ANSP data refer to incursions / collisions. As well as incursions / collisions, ground handling also captures FOD occurrences, which make up almost 40.0% of the data. The distributions of occurrence types for the airlines and airport operators are similar, with predominantly incursions and FOD and a very small percentage of excursions being reported. The regulators, on the other hand, show a very different frequency distribution of occurrence types, with almost 38.0% of reported accidents / incidents being excursions.

These differences are a reflection of the stakeholder perspectives that are represented through the data, and the associated differing interests and responsibilities of the stakeholders. For example, ATC is always obliged to report an incursion. It is ATC's responsibility to provide the required separation between two aircraft, or an aircraft and a V/PD, to monitor the traffic and report infringements. Excursions and FOD on the other hand are the responsibility of airport operators and pilots to report, unless ATC contributed to their occurrence, or the occurrence interrupted the flow of normal operations.

In addition, the reported occurrence types differ depending on the stakeholder's function in the ATM system. For example, Chapter 6 has indicated that regulatory databases are underreported. Although most regulators claim that they capture every safety-challenging situation, in reality, most of the time, stakeholders report only the more serious occurrences to the regulators. Excursions often result in serious incidents or

accidents and, therefore, the majority of these occurrences will be captured at the regulatory level. On the other hand, a FO(D) occurrence that does not challenge the safety of the operations is unlikely to be reported to the responsible regulator, and often stays at the airport level, or airline level if the FO(D) has had an impact on the flight operations.

Furthermore, the physical area of responsibility of the stakeholders influences the type of occurrences they capture. For example, regulatory bodies provide the regulations for the whole country, including small regional airfields, whereas ATC is only responsible for controlled airports. Small regional uncontrolled airports will not experience incursions for example, as aircraft do not have to contact ATC to ask for clearances. Therefore, these airports will mainly report excursions and FOD.

Overall, the results indicate that it is necessary to collect data reflecting the different perspectives of aviation stakeholders in order to capture all occurrences on the airport surface in equal measure.

Next, the data was tested for associations between the stakeholders and the causal factors. Causal factors category 5, which captures the regulatory system, was excluded from the analysis due to the very low frequency of regulatory factors extracted from the data.

There was a significant association between the type of stakeholder and the causal factors at the first taxonomy level X^2 (15) = 1315.527, p < .001 (Figure 100) and Cramer's V (.201, p < .001) indicates a moderate association.

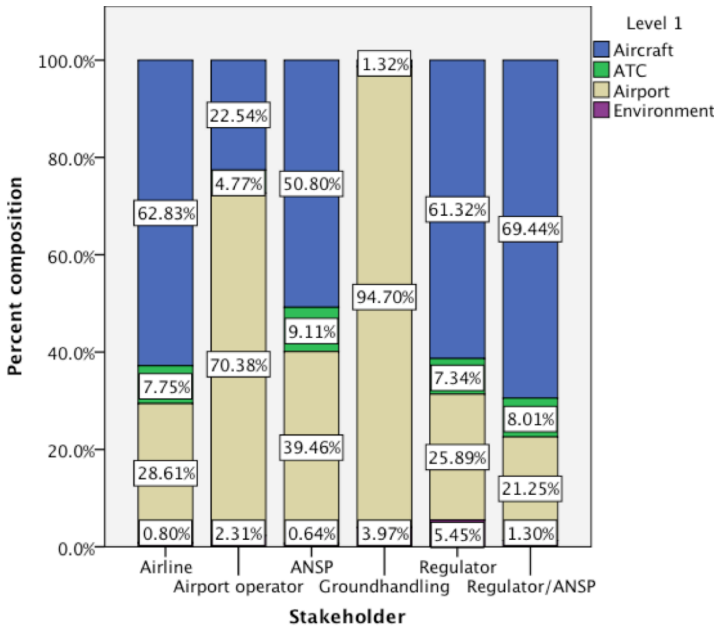


Figure 100: Causal factors (Level 1) per stakeholder

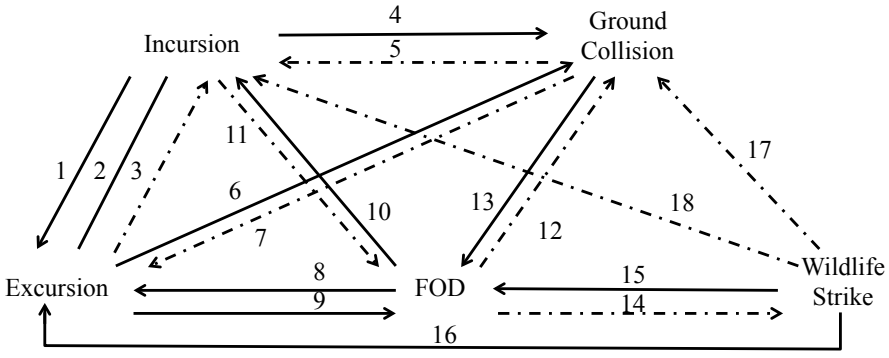
These two tests, together with the preceding descriptive analysis, prove that if safety risk mitigation strategies are developed from the perspective of a single stakeholder they will always be biased. This is because different stakeholders collect different occurrence types and therefore capture different causal factors. Future reporting systems should therefore allow for the integration and sharing of safety data. This could be achieved through either centralised databases, or a network approach, i.e. a system of data sharing in which the appropriate linkages between the individual stakeholders are made.

8.2 Cross-Occurrence Analysis

After determining the causes for airport surface safety occurrences the relationships between the different occurrence types were analysed.

8.2.1 Relationships Between Occurrence Types

Figure 101 provides an overview of how the occurrences influence each other. The black lines show interactions that have been identified through the data analysis, while the dashed lines indicate indirect connections. Indirect connections are relationships derived from the data. That is, in these circumstances the data did not contain instances where one occurrence type directly caused another, but it did indicate an indirect connection. To illustrate the interactions further, examples for each relationship have been extracted from the safety data and are given below.



Bold lines: direct interactions; dashed lines: indirect interactions

Figure 101: Influence diagram occurrence types

1. Incursion causing an excursion: The data analysis identified situations whereby an aircraft infringed onto a runway and caused the excursion of another aircraft.
2. Occurrences that are both, incursions and excursions: The analysis revealed occurrences that could be classified as both excursions and incursions. For example, a pilot intentionally left the taxiway and took a short cut through the other surface areas (i.e. grassland) in order to reach the apron more quickly. In this case the aircraft left the taxiway (i.e. excursion) and was in a position on the airport surface where he / she was not supposed to be (i.e. incursion).
3. Excursions causing incursions: There was no example of an excursion causing an incursion identified in the data and therefore no direct link. However, the data contained occurrences where incursions happened due to runway / taxiway closures (e.g. caused by the pilot not being aware of the closure). After the occurrence of an excursion the affected surfaces will typically be closed, and this in turn may cause incursions.
4. Incursions causing ground collisions: Collisions are extreme cases of incursions. Thus, every collision will be an incursion before it becomes a collision.
5. Ground collisions causing incursions: There was no example in the data where a collision caused an incursion. However, in theory, in a similar way to which excursions can lead to an incursion, collisions also will result in surface closures, which can then provoke incursions.
6. Excursions causing ground collisions: The safety data showed that if aircraft veer off the runway they can collide with other aircraft, vehicles, or surface infrastructure.
7. Ground collisions causing excursions: There was no direct link in the data that showed collisions leading to excursions. As mentioned before, however, surface closures that result from collisions could lead to excursions, when an aircraft needs to avoid the closed surface.
8. FOD causing excursions: Foreign objects on the airport surface can lead to excursions, for instance when the FO causes a tire burst.
9. Excursions causing FOD: An excursion that results in physical damage to the aircraft can cause FOD.
10. FOD causing incursions: FOD can also lead to incursions, when vehicles trying to pick up FO infringe onto a runway / taxiway without authorisation.

11. Incursions causing FOD: There is no direct link between incursions and FOD. The analysis, however, showed that incursions can cause an excursion and that excursions can lead to FOD.
12. FOD causing ground collisions: The data did not contain any direct link showing that FOD occurrences cause collisions. As shown in 8. FO can cause excursions and an excursion can lead to a collision. Thus, there is an indirect link between FOD and collisions.
13. Ground collisions causing FOD: Collisions cause FOD when physical damage occurs as a result of a collision.
14. FOD causing wildlife strikes: Similarly, there was no direct link found between FOD and wildlife strikes. However, the data contained FOD occurrences involving rubbish / garbage on the surface. As shown in the literature (e.g. Transport Canada, 2002; UK Civil Aviation Authority, 2008a) garbage is also a wildlife attractant.
15. Wildlife strikes causing FOD: Wildlife can lead to FOD when wildlife remains are on the airport surface.
16. Wildlife strikes causing excursions: As seen in the data, wildlife can also cause excursions, for instance, when birds are ingested into the engine, which results in an engine failure and can lead to an excursion.
17. Wildlife strikes causing ground collisions: There was no direct link found in the data between wildlife and collisions. However, the data showed that wildlife can cause excursions and excursions can result in a collision. Thus, there is an indirect link between wildlife and collisions.
18. Wildlife strikes causing incursions: Finally, the data did not contain any situations whereby a wildlife strike causes an incursion. However, it has been shown that wildlife can lead to FOD and that FOD can cause an incursion. Thus, there is an indirect link between wildlife and incursions.

Only two combinations of occurrence types were identified that do not share a causal relationship:

- An incursion leading to a wildlife strike; and
- A collision leading to a wildlife strike.

This analysis proved that the occurrences do not happen in isolation and can follow complex event chains (e.g. wildlife remains can cause FOD, which in turn can cause an

excursion). As the occurrence types interact in a complicated manner, any assessment of the safety of airport surface operations must integrate them all.

8.2.2 Shared Causal Factors

The occurrence types were also analysed for shared causal factors and Figure 102 shows the results. The data for collisions and incursions were aggregated. The analysis identified shared causal factors between incursions / collisions, excursions, and FOD. Based on the data, there were no shared factors between these three occurrence types and wildlife strikes.

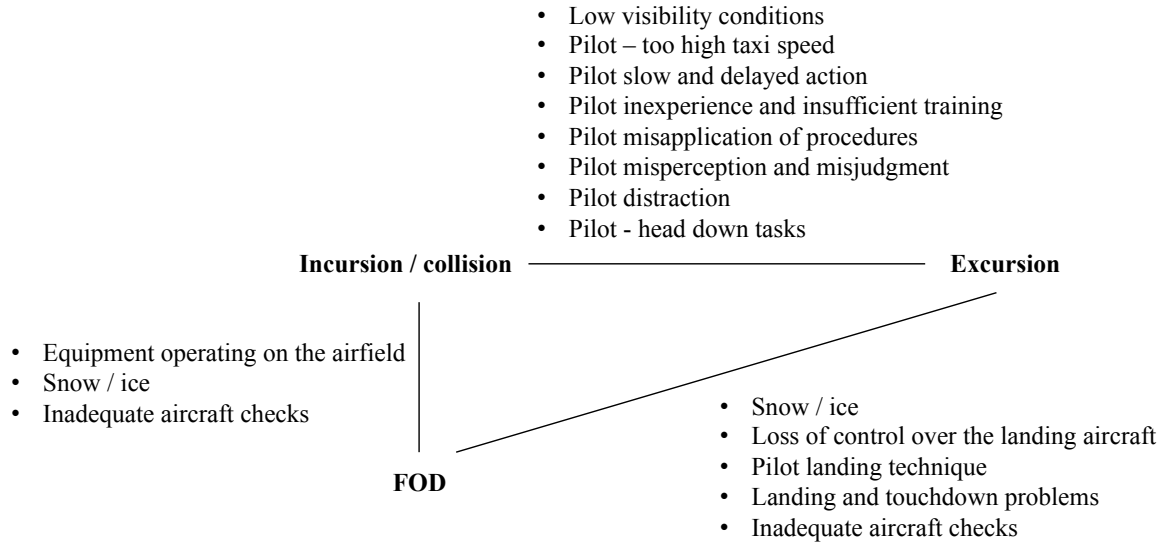


Figure 102: Influence diagram of shared causal factors

8.3 Discussion

The previous chapter showed that the causal factors were subject to national variations and in addition this chapter identified that there were variations within stakeholder types, i.e. the same type of stakeholder (e.g. regulator) can capture different causal factors. Also, the variety of causal factors captured across the databases (i.e. number of different causal factors extracted from each database) differed.

It was also shown that each stakeholder adds a unique perspective to the understanding of airport surface safety, i.e. the analysis allowed the extraction of factors from some databases that were neither captured in others nor in the literature.

The analysis in Chapters 7 and 8 showed that the causal factors vary and that they are a function of:

- The underlying national air traffic system and airport infrastructure,
- The underlying regulations and operational procedures,
- The reporting system and safety culture, and
- The viewpoint of the aviation stakeholder that is represented.

Overall, it can be concluded that the piecemeal approach is sub-optimal in capturing the total system safety. An integrated safety assessment of airport surface operations is only possible by combining the different stakeholder viewpoints.

Furthermore, the piecemeal approach implies that safety risk mitigation strategies will always be biased depending on the viewpoint of the stakeholder who initiated the control measures. For instance, the 'European Action Plan for the Prevention of Runway Incursions' (The European Organisation for the Safety of Air Navigation, *et al.*, 2011) depicts a consensus of subject matter expertise from major European ANSP's. It provides recommendations for the mitigation of runway incursions for all aviation stakeholders. The ICAO's 'Manual on the Prevention of Runway Incursions' (International Civil Aviation Organization, 2007), which is based on the EUROCONTROL developments, has a similar intention. Hence, it makes the recommendations in Europe effective on a global level. ICAO's global guide contains an initial reporting form for runway incursions. Through its biased development based on SME opinion it fails to capture various factors that are critical in the context of runway incursions. For example, the manual does not account for the following factors of the new taxonomy: 311-318, 321, 322, 325, and 327 in the context of V/PD. This example is typical for the industry and has implications for the data collection and reporting.

Also, the use of data from just one stakeholder to channel risk mitigation efforts can be misleading due to the different distributions of causal factors they capture. Using only a single data source to guide safety risk mitigation strategies can only be valid if the initiative targets the improvement of a particular stakeholder's operation (e.g. ANSP uses ATC data to develop risk mitigation strategies for ATC). Otherwise, risk mitigation

strategies should be developed based on an integrated understanding of the subject matter, for which data sharing is the first step.

The analysis further identified that the different occurrence types are highly interactive, i.e. one occurrence type can be the cause for another one. The KPIs currently used in the industry to measure airport safety performance (as introduced in Chapter 2 section 2.4.1) focus on high-level measures, such as aggregated occurrence numbers. To capture the dynamics of surface safety these KPIs should capture also the interactions of occurrences.

In addition, the comparison of causal factors underlying the different accident / incident types identified some common causes. Hence, in this context, safety risk mitigation strategies would benefit from targeting surface safety as a whole. This will be discussed in more detail in the next chapter (section 9.3.2). As the literature review showed, risk mitigation programmes are currently designed to prevent single occurrence types. If they were designed for surface operations in general, awareness for all accident / incident types could be raised within one initiative. In turn, this would lead to more cost-effective solutions. In fact, the SMEs in Norway pointed out in a structured communication that in the past they focused so much on the prevention of incursions that they now experience more excursions (Structured communication with Safety Investigatiors Avinor AS ANSP, June 2011). This example highlights well the danger associated with focusing too much on one aspect of surface safety.

8.4 Stochastic Elements in the Airport Surface System

The results of the safety data analysis were used to validate the initial process model of normal airport surface operations and to identify the stochastic elements in the airport surface system architecture developed in Chapter 3 Figure 28.

To validate the initial process model, the information extracted from the occurrence reports was used. For instance, a report from the FAA RI database states the following: “Local Control (LC) instructed an a/c to taxi into position and hold (TIPH) RWY 33. The a/c then departed on RWY 33 without clearance. No conflicts reported.” From this narrative the following information can be extracted:

- There was a taxi process;
- At some point the aircraft transferred from the taxiway to the runway;

- The instruction taxi into position and hold means that the aircraft should taxi out onto the runway into take-off position and to hold until the final take-off clearance is given by ATC (i.e. that a clearance for take-off is required).

This information conforms to the tasks described in the initial process model (Table 5).

In a second example, "a truck, towing a trailer, crossed RWY 10 at TWY D1 without authorisation. No conflicts reported." This report provides the following information: a vehicle was taxiing and transferred from a TWY to a RWY. For this a clearance would have been required. The tasks 'taxiing on TWY', 'obtaining clearance', and 'entering RWY' conform to V/PD tasks outlined in the initial process model (Table 6).

Occurrence reports where the descriptive narrative did not fit the initial process model were used to identify the stochastic elements in the airport surface system architecture. Stochastic elements are links that do not exist in theory, but appear in reality. The analysis revealed four stochastic elements as follows:

1. Customers can influence airport surface operations:

In theory, customers (e.g. passengers) are in contact with various service providers, e.g. the airline for booking flights, or the airport operator for information purposes. Passengers, however, are not allowed onto the airport surface unless they are sitting in an aircraft. The data revealed situations whereby passengers infringed onto the airport surface. In one instance a passenger was leaving the aircraft and running out on the surface. In another one a passenger lost some papers and was running onto the taxiway to chase them.

2. Local communities can influence airport surface operations:

In theory members of the local community are not in contact with the physical infrastructure of the manoeuvring area or the actors upon it (e.g. pilot, V/PD, ATC). However, the analysis of safety data revealed circumstances where members of the local community infringed onto the airport surface. Examples found in the safety data include:

- Children crawling under a gate that was used for construction purposes and infringing onto the airport surface;
- A mentally ill person escaped from a nearby hospital, jumped over the perimeter fence and infringed the manoeuvring area;
- Perimeter fence being snowed under and pedestrians walking over it without realising their infringement onto the airport surface; and

- An ambulance vehicle transporting an injured person driving into the protected area of the airport and onto the manoeuvring area without clearance in order to get to an ambulance helicopter.

3. The land use surrounding the airport can influence the operations on the airport surface:

Under normal circumstances, the land use surrounding the airport does not influence the operations on the manoeuvring area. For instance, whether fields, forest, or local communities are established next to the airport does not influence the operations of a pilot, V/PD, or ATC. However, there are situations in which this is not true; for example:

- One airport reported increased bird activity due to a fishing industry next to the airport. This disturbed the operations as increased wildlife removal activities were necessary;
- Birds can drag objects from the surrounding land onto the manoeuvring area, which causes disruptions. Examples found in the safety data include e.g. graveyard lights, golf balls, and crab shells. These examples actually depict a combined influence of the environment (wildlife) and the surrounding land use on airport surface operations.

4. There are stochastic interfaces between the apron and the airport surface:

The airport surface system architecture shows an interface between the airport surface and its surrounding infrastructure and operations (e.g. apron). Under normal circumstances, the operations of apron and airport surface influence each other. For instance, a pilot starts his / her operations on the apron and transfers during taxiing onto the manoeuvring area. The data revealed, however, that there are interfaces between apron and manoeuvring area that are not expected under normal circumstances (i.e. normal operations). These include:

- Pushback onto a live taxiway;
- Vehicles being parked on the line that separates the apron and manoeuvring area;
- Handling equipment infringing onto taxiways; and
- Situations in which V/PD do not wait for slower vehicles in front of them and overtake these vehicles by crossing the line between apron and manoeuvring area.

Overall, the airport surface system architecture has been updated by adding four links to the model of the airport surface system architecture, which are shown in Figure 103 in red.

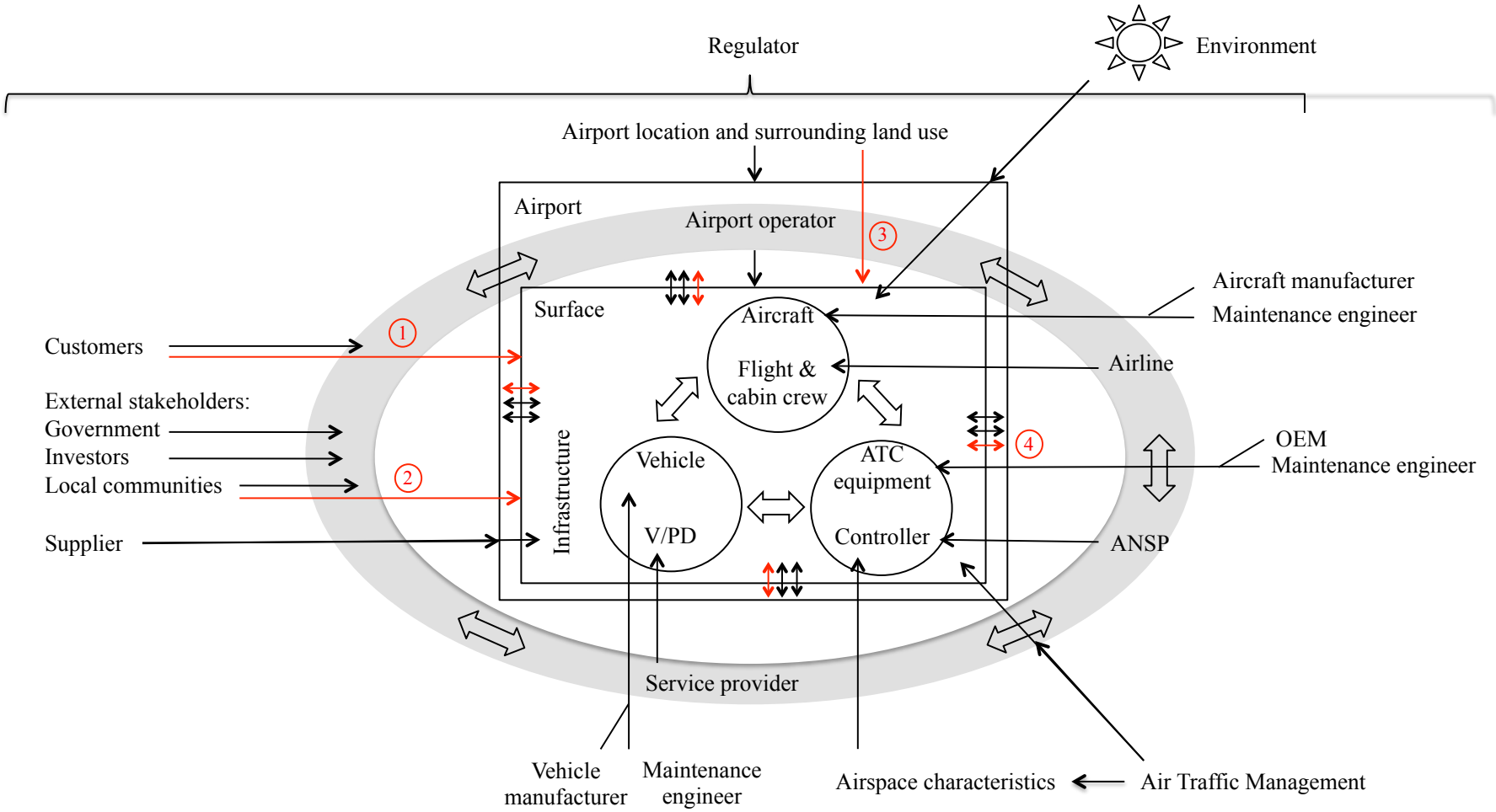


Figure 103: Stochastic elements in the airport surface system architecture

In addition, the analysis has identified a stochastic interface between the stakeholders. To recap, Chapter 3 specified communication as the interface between the various actors under normal circumstances. The safety data analysis revealed a second interface: the location, i.e. one actor can influence another party in the same location. The following two examples will clarify this. An occurrence report extracted from the FAA RI database states: "Ground Control (GC) issued an a/c 1 taxi instructions to RWY 33 via TWY A-2, hold short of RWY 33. Pilot read back the taxi instructions but not the hold short and entered RWY 33 via TWY A-2. An a/c 2 was just taxiing onto RWY 33 approach end with a take-off clearance as the a/c 1 entered at A2. Local Control (LC) noticed the conflict and cancelled the a/c 2's take-off clearance. Closest horizontal separation reported was 4,376 feet."

The following information can be extracted from this occurrence report:

- An aircraft (a/c 1) is instructed to taxi to a runway and to hold short of it;
- However, the pilot entered the runway and came in conflict with another aircraft (a/c 2) that was already on the runway and cleared to take-off;
- Through this infringement a/c 1 influenced the actions of the second actor (a/c 2), as ATC cancelled its take-off clearance.

Another report contains the following occurrence description "an airport vehicle was observed on TWY Bravo and requested clearance to retrieve FOD near TWY B4. Ground Control instructed the airport vehicle to hold short of RWY 30. The vehicle crossed the hold lines for RWY 30 and conflicted with a/c crossing landing threshold RWY 30. Ground Control instructed the vehicle to immediately return across the hold lines. Closest proximity was more than 5,000 feet horizontal after the a/c landed and airport vehicle cleared the hold lines."

Broken down, the report contains the following information:

- A V/PD was on the taxiway and instructed to hold short of the runway;
- However, the V/PD crossed the hold line and conflicted with an a/c; i.e. the V/PD influenced the operations of the a/c and ATC by infringing onto the runway.

These two examples highlight that if an actor infringes into an area, this can influence the actions of those actors that are operating in respect to that location. The locations of the various stakeholders during normal operations have been described in Chapter 3 section 3.2.

In summary, this last section refined the process model through:

- Validation of the initial process model;
- Identification of stochastic relationships between the actors / components; and
- Identification of stochastic interfaces.

8.5 Summary

This chapter has analysed the causal factors of airport surface accidents and incidents at the cross-State level. A novel cross-stakeholder comparison of the factors proved that the various stakeholders capture unique viewpoints and that these must be combined in order to provide for an integrated risk assessment of airport surface operations. The results of the data analysis were then used to update the airport surface system architecture and to identify its stochastic elements. This information was used to refine the initial process model and therefore contributed to the fulfilment of the second research objective.

The next chapter summarises the causal factors identified in Chapters 5, 7 and 8 in a new taxonomy. In addition, the refined process model is validated and both parts (the taxonomy and the process model) are merged resulting in a macroscopic scenario tool.

9 A Macroscopic Scenario Tool for Airport SMS

The previous chapters have captured the architecture (Chapter 2) and operational aspects (Chapter 3) of airports. Chapters 5 to 8 subsequently, identified the factors that lead to occurrences on the manoeuvring area. This information was used to identify the stochastic elements in the airport surface system architecture leading to an update of the airport surface system architecture. To ensure that the process model is applicable to all other airports and not just those used for its development, external validation is required. This chapter presents the process and results of the external validation of the process model.

This chapter also concludes the determination of causal factors by summarising the factors into a taxonomy that supports the data analysis function of SMS, providing a robust basis for data analysis. After the airport surface operations have been modelled and the drivers to safety identified (causal factors), the results are combined, resulting in a macroscopic scenario tool which supports the management of change (i.e. safety assurance), training and education, and safety communication (i.e. safety promotion) functions of the SMS.

9.1 Process Model of Airport Surface Operations

9.1.1 Methodology

External validation was accomplished with Subject Matter Experts (SMEs). They were asked in face-to-face interviews to systematically assess it and to comment on its validity. The following SMEs were chosen for the reasons discussed below:

1) Validation of the airport authority model, airport infrastructure, V/PD model, interfaces, and airport surface system architecture with:

- The Airfield Operations Superintendent at a major U.S. airport (LAX),
- The Head of Health, Safety and Regulatory Compliance of a medium-sized UK airport (LPL), and
- The ATC Tower Supervisor of a small Norwegian airport (BOO).

These airports were chosen because they provide a mix of U.S. and European airports, of different sizes in terms of infrastructure, aircraft movements and passenger boardings, as well as different ownership structures. In addition, these airports represent different national operational practices, procedures and regulations. SMEs in senior positions with a minimum of 15 years service were chosen in order to ensure a high-level of relevant experience.

2) Validation of the ATC model, interfaces and airport surface system architecture with:

- A civil ATC Tower controller with working experience at a major European airport and the Maastricht Upper Area Control Centre (MUAC), and
- A military ATC Tower controller with working experience at European military airports and MUAC.

The internal validation of the process model (discussed in Chapter 3 section 3.1.4) used a U.S. tower supervisor. To make the model valid across borders and air traffic control units (i.e. upper airspace), a European perspective was sought for external validation. In addition, a controller with military experience allowed validation of the model from a different perspective. Both SMEs had more than 15 years of experience in ATC.

3) Validation of the pilot model, interfaces and airport surface system architecture with:

- A Captain of a European airline and Safety Manager.

Similar to the ATC perspective, a U.S.-based chief pilot was used to validate the initial process model internally. Therefore, to capture the European perspective, a Captain and

Safety Manager of a European airline with more than 15 years of relevant experience was consulted.

9.1.2 Baseline Model for Airport SMS

The SMEs confirmed the validity of the model and the final airport surface system architecture is shown in Figure 104. The stakeholders are highlighted in blue font and infrastructure in green. Blue arrows represent interactions between stakeholders and red arrows the stochastic elements of the system. Furthermore, other external factors (e.g. weather) are highlighted in black font. The initial process model developed in Chapter 3 represents an ideal system that assumes 'normal operations' in which e.g. the actors do not make mistakes and the infrastructure / equipment is not subject to malfunctions (the assumptions were specified in section 3.1). In contrast to that, the final process model presented in this chapter does no longer assume 'normal operations'. It is therefore rather a representation of the reality of surface operations.

9.1.3 Application

The developed model captures the components (including physical infrastructure and stakeholders) and interactions of the airport surface system and serves as baseline model for airport SMS. As introduced in Chapter 4, a Safety Management System (SMS) requires the analysis of all system components and their interactions. Therefore, the new model can be used to facilitate safety assessments of surface operations, because it shows the relevant stakeholders / components involved in airport surface operations and their linkages.

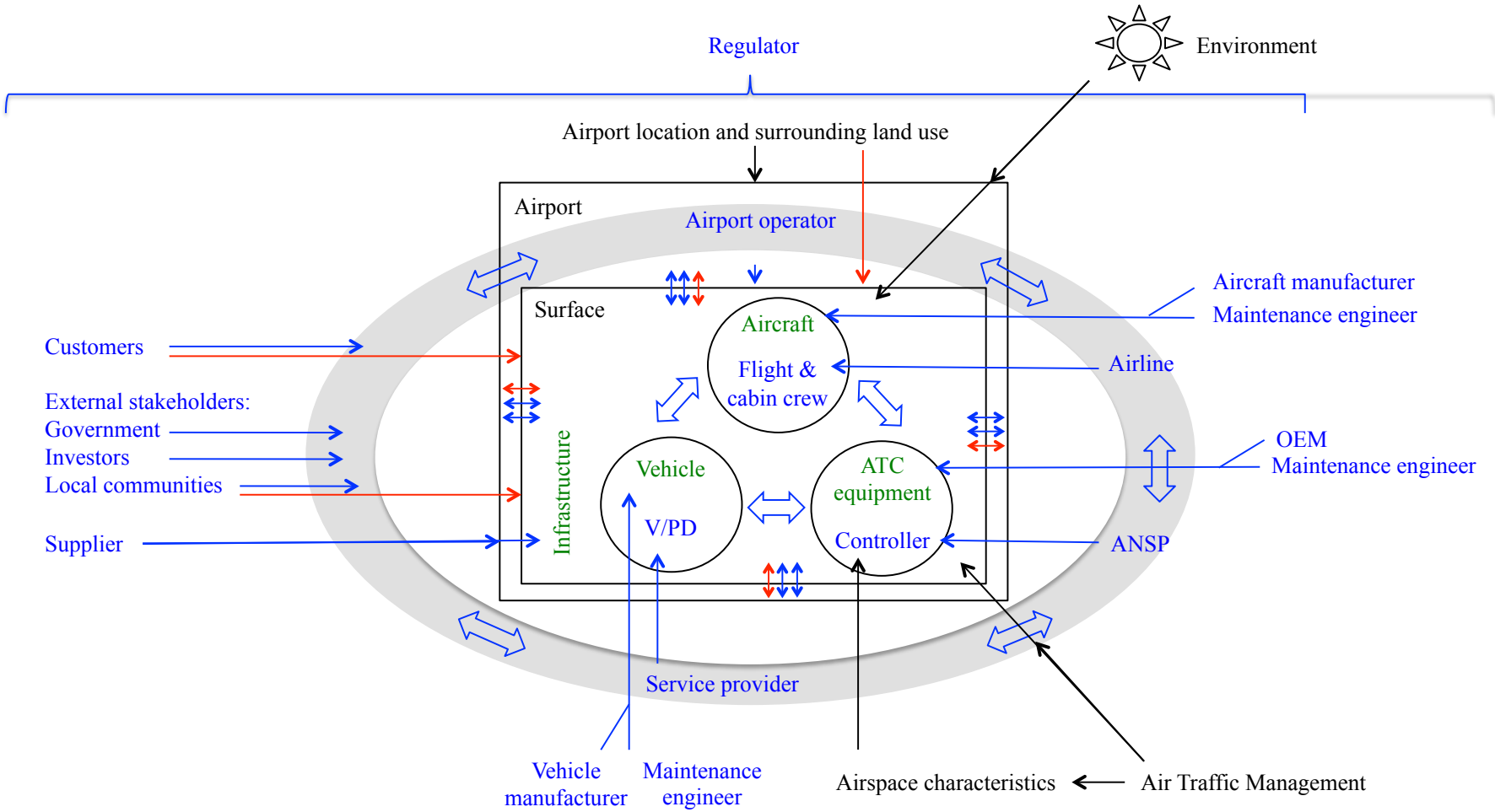


Figure 104: Validated airport surface system architecture

9.2 A New Taxonomy of Causal Factors Underlying Airport Surface Safety Occurrences

After modelling the operations on the airport surface, this thesis analysed the ways in which the system can fail. Chapters 5 to 8 identified the causal factors of accidents and incidents and the following section summarises them in a new taxonomy.

9.2.1 Methodology

The construction of the new taxonomy involved two steps: development and validation. The methodology for the analysis of causal factors and the framework for the development of the taxonomy were presented in Chapter 6 section 6.7. The next section builds on these to construct the final template. A number of reliability and validity checks have been undertaken to ensure that the application of the classification system produces valid and reliable results.

9.2.1.1 Taxonomy Development

The taxonomy has been developed using the analysis of causal factors in Chapters 5 to 8. Template analysis was applied, since this is a flexible technique which allows for the incorporation of different research methods. First, an initial template was constructed using the causal factors extracted from the literature. Subsequently, this template was refined using the previous analysis of 12 safety databases reflecting the perspectives of airport operators, ANSPs, airlines, ground handling companies and regulators in Europe, North America and Oceania. To complement this analysis both interviews and observations were conducted to better understand the causes of airport surface accidents and incidents. In a final step, the taxonomy was validated using statistical analysis and input from SMEs as detailed in the next section. Figure 105 summarises the methodology adopted for the development of the taxonomy.

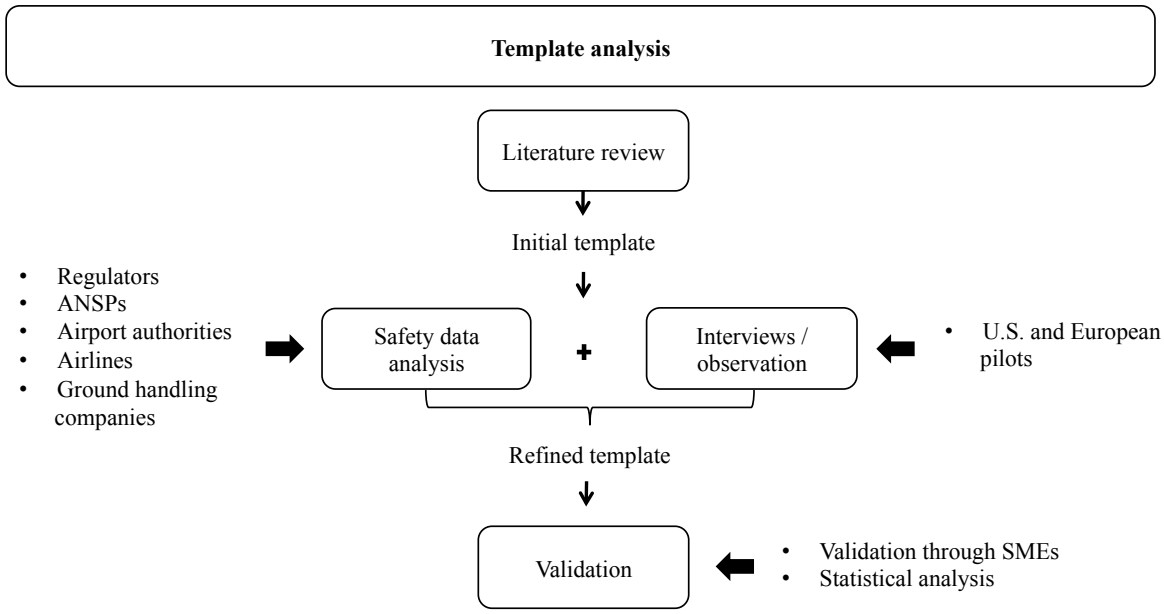


Figure 105: Methodology for taxonomy development

9.2.1.2 Taxonomy Validation

To ensure that the taxonomy produces valid results, a validation strategy has been developed based upon internal and external validity checks. Internal validity measures how well the taxonomy captures what it intended to capture, i.e. how well the taxonomy represents the reality of what is measured. To test for internal validity, construct, content and criterion validity were analysed. External validity refers to the extent to which the results can be held to be true for other cases. Therefore, the taxonomy was applied to different datasets that have not been analysed before. In addition, reliability checks were conducted to ensure that the taxonomy has been developed consistently, is of good quality and produces robust findings (Saunders*, et al.*, 2007).

- ***Reliability***

To ensure a consistent taxonomy development the data coding (i.e. extraction of the causal factors from the descriptive narratives) was checked for reliability using Cohen's Kappa inter-rater reliability test. Cohen's Kappa (κ) computes the extent of agreement between two raters taking into account the possibility of agreement occurring by chance. It is computed as follows:

$$\kappa = \frac{p - p_e}{1 - p_e} \quad (8)$$

where p is the proportion of units where there is agreement and p_e the proportion of units which would be expected to agree by chance. If the raters are in complete agreement then κ takes on a value of 1. On the other hand, κ is 0 if there is no agreement other than that which would be expected by chance (University of York, 2012). The coding can be accepted as reliable if the agreement rate is at least .70 (Fleiss*, et al.*, 2003).

Cohen's Kappa inter-rater reliability has been computed for the first three levels of the taxonomy, as commonly practiced in aviation accident analysis (e.g. Wiegmann and Shappell, 2003). To establish inter-rater reliability, three independent qualified raters were each asked to code a sample of 300 randomly selected occurrences. In accordance with previous research (e.g. Jarvis and Harris, 2008) each rater was given 100 occurrence reports to analyse at each level of the taxonomy. Each rater was asked to analyse the descriptive narratives of 100 reports and to assign a code from the first taxonomy level. In case more than one causal factor could be extracted from a report, several codes from the first taxonomy level had to be recorded. Subsequently, each rater was asked to code 100 occurrences using codes from the second, and third levels of the taxonomy, respectively. The occurrences to be coded by the raters were randomly selected at each level, so that each rater analysed a total of 300 different occurrences.

The three raters were chosen based on their academic background in aviation safety (i.e. two at Master's-level and one at Ph.D.-level) and each rater was given a data set from a randomly selected regulatory body (i.e. UK CAA, U.S. Northeast, and U.S. Western-Pacific Region). Regulatory datasets were chosen because they capture the greatest variety of causal factors, given that all aviation stakeholders are required to report into these systems.

Cohen's Kappa requires the analysis of reports falling into each of the possible outcome categories. For example, the first taxonomy level has five categories (i.e. aircraft operations, ATC, airport operations, environment, regulations), and, therefore, at least one occurrence that falls into each of these categories should be analysed. This principle was retained as far as practically possible. However, in some cases it was necessary to exclude causal factor categories from the analysis (i.e. low populated groups of causal factors, factors identified through literature, interviews, observations).

Whilst all possible causal factor categories have been considered at the first and second taxonomy levels, reliability at the third taxonomy level was checked using case studies, i.e. a branch of the taxonomy was randomly selected and analysed for each data set. Figure 106 provides an example of the study design for the UK CAA data. Reliability checks for the UK data included the coding of 100 occurrence reports falling into four categories (highlighted in orange) at the first taxonomy level by the author and an independent rater. Regulatory factors were excluded from the analysis due to their low frequency of occurrence. Similarly, at the second taxonomy level, 100 occurrence reports falling into eight categories of causal factors (highlighted in green) were considered. Finally, inter-rater reliability between the independent rater and the author was established using 100 reports falling into seven categories of pilot human-related factors (highlighted in blue) at the third taxonomy level. The categories used to check the reliability of the coding of the U.S. Northeast and U.S. Western-Pacific Region datasets are shown in the results section 9.2.2.1 on reliability checks.

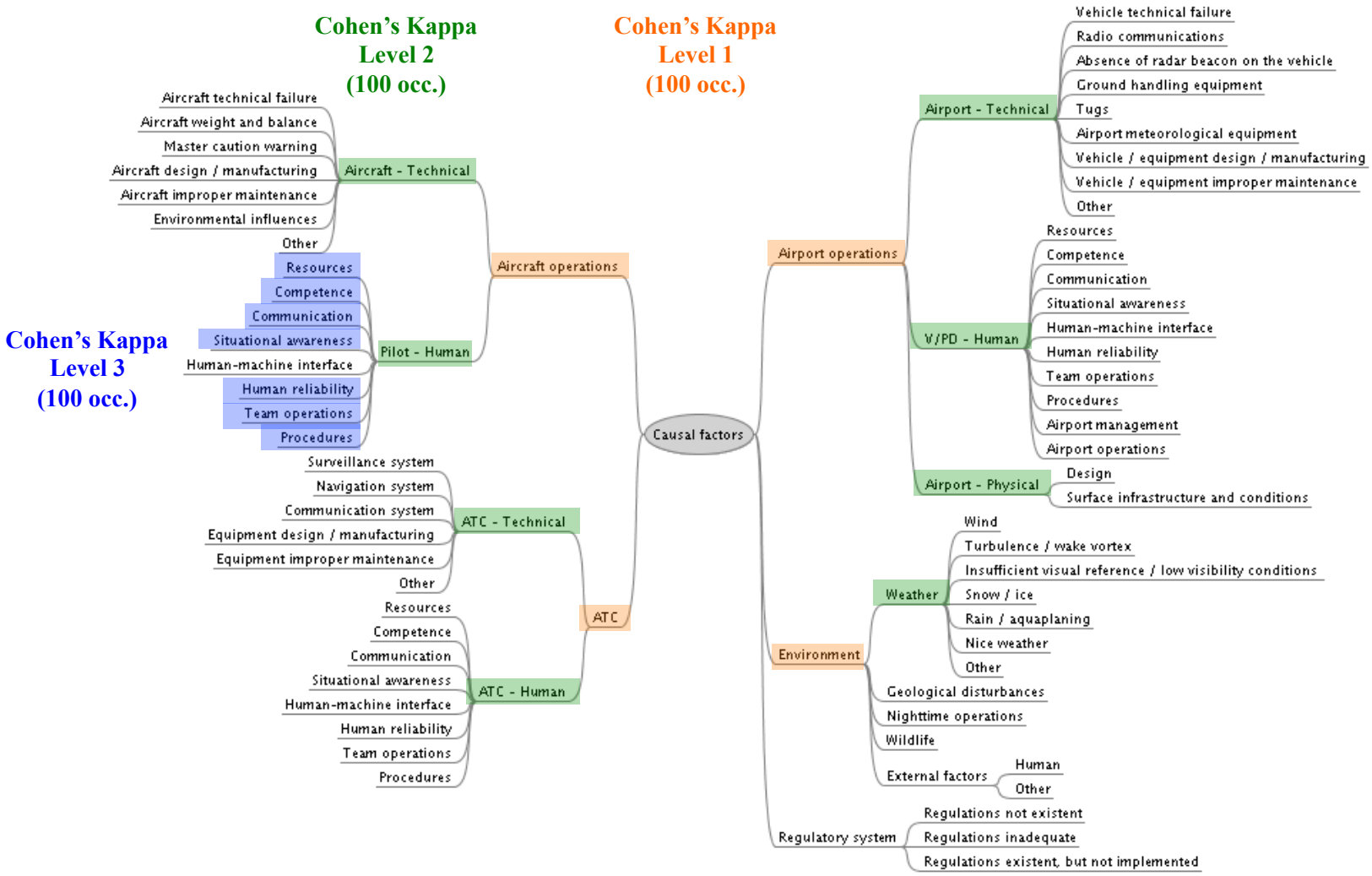


Figure 106: Taxonomy reliability checks (Levels 1-3) UK CAA

- ***Construct Validity***

Construct validity indicates the extent to which the taxonomy actually measures what it theoretically should, i.e. how closely the taxonomy reflects the underlying theoretical model (Carmines and Zeller, 1979; Saunders*, et al.*, 2007). The airport surface system architecture has been modelled in Chapter 3 (section 3.2.9) and validated in Chapter 8 (section 8.4). If the taxonomy is a good measure of the causal factors underlying airport surface safety occurrences, it should reflect the failures of all system components.

The evaluation of construct validity involved matching the identified causal factors against the airport surface system architecture. This allowed the evaluation of whether the taxonomy captures all components of the system description.

One of the tenets of SMS is that each component of a system can fail and therefore each component needs to be analysed. An association between system components and causal factors exists in theory and statistical analyses of the internal structure of the taxonomy were conducted to test for this. To this end the data was tested for associations between stakeholders (i.e. system components) and causal factors using the Pearson's Chi-Square test.

- ***Content Validity***

Content validity refers to the selection and representativeness of the sample and is an estimate of how well the taxonomy encompasses the theory, i.e. whether the taxonomy assesses all facets of a theoretical construct (Carmines and Zeller, 1979; Saunders*, et al.*, 2007).

To achieve content validity, the safety data has been selected based on requirements derived from the descriptive model of the airport surface system developed in Chapter 3. The model identified five main stakeholders involved in airport surface operations (i.e. airport operator, ANSP, airlines, ground handling companies and regulator) and the data has been selected so as to represent all perspectives. The data choice was validated with senior safety experts from EUROCONTROL, the FAA and major ANSPs in Europe, as described in detail in Chapter 6 section 6.2.2. In addition, a variety of research methods have been applied in order to ensure that the causal factors are understood in detail.

A further aspect of content validity is face validity, which estimates the extent to which the taxonomy appears to be a good measure (Carmines and Zeller, 1979; Saunders*, et al.*, 2007). To achieve face validity, the final structure of the taxonomy was validated with SMEs representing each of the relevant stakeholders. The SMEs were chosen to fulfil the following criteria:

- SMEs from organisations with a reputation for a good safety culture;
- SMEs representing the different stakeholder perspectives;
- SMEs both from organisations that did, and those that did not, provide the safety data used for developing the taxonomy;
- A mix of SMEs from the U.S. and Europe; and
- Professional expertise of the SME (e.g. supervisors instead of staff on the frontline).

The SMEs were presented with the taxonomy and given sufficient time to review it and asked to comment on its structure, the appropriateness of the causal factors identified, missing elements, and terminology. The following ten SMEs validated the taxonomy and the results are discussed in section 9.2.2.3:

- A Chief Pilot of a U.S.-based airline and the Safety Manager of a European airline;
- A FAA Tower Supervisor, a European civil ATC controller, and a European military ATC controller;
- Two Airfield Superintendents from two major U.S. airport operators and a Safety Manager from a European airport authority; and
- The Head of Safety Regulations at EUROCONTROL (retired) and a Senior Safety Expert from the FAA.

- ***Criterion Validity***

The most difficult aspect of validation is criterion validity, which is concerned with the question of whether the taxonomy produces valid results, i.e. whether it measures what it says it would measure. This can be thought of as a 'predictive validity', which assesses whether the taxonomy can predict what it should theoretically be able to predict (Saunders*, et al.*, 2007).

New datasets were gathered from the safety data providers and subsequently analysed. Three datasets were requested since this allowed 25.0% of the data to be tested for

criterion validity. In order to analyse different stakeholder perspectives, three organisations: Avinor ANSP (ANSP), OSL (airport operator), and the UK CAA (regulator) were asked for their data for 2011. The datasets were pre-processed as before (refer back to Chapter 6 section 6.6 for further details) and analysed for causal factors. If the taxonomy is valid it should capture all causal factors extracted from the data. A total of 100 randomly selected occurrence reports were analysed for each database.

- ***External Validation***

External validity refers to the extent to which the taxonomy is applicable to new datasets (Saunders*, et al.*, 2007). In order to achieve external validity, the taxonomy was applied to three new datasets. The taxonomy was tested against ANSP data from the U.S. Great Lakes Region,[15] for which data for 2005 to 2009 was available from the FAA RI database. A hundred randomly selected occurrence reports were analysed using the new classification system. In addition, Signature's database contained 455 reports of accidents / incidents that occurred outside the U.S. and UK (i.e. Europe and the Bahamas) between 2007 and 2011. These were pre-processed as outlined in Chapter 6 section 6.6.3 in order to identify those reports that refer to airport surface occurrences. Five relevant occurrences were identified and subsequently analysed using the new taxonomy. Moreover, five detailed accident and incident reports from a European regulator (i.e. not the UK CAA and not the CAA-Norway) were available, which allowed the application of the taxonomy to a completely new data set. These data sets were chosen because they represent three different stakeholder perspectives and complement the viewpoints that were analysed to achieve criterion validity.

A recent, or new, dataset from an airline was not available. To ensure that the taxonomy is valid from a pilot / airline perspective, the taxonomy's content was checked by a Chief Pilot from a U.S.-based airline and the Safety Manager of a European airline. Figure 107 summarises the methodology for taxonomy validation including the aim of each step, the corresponding methods, and their implementation.

[15] Illinois (IL), Indiana (IN), Michigan (MI), Minnesota (MN), North Dakota (ND), Ohio (OH), South Dakota (SD), Wisconsin (WI) (Federal Aviation Administration, 2000)

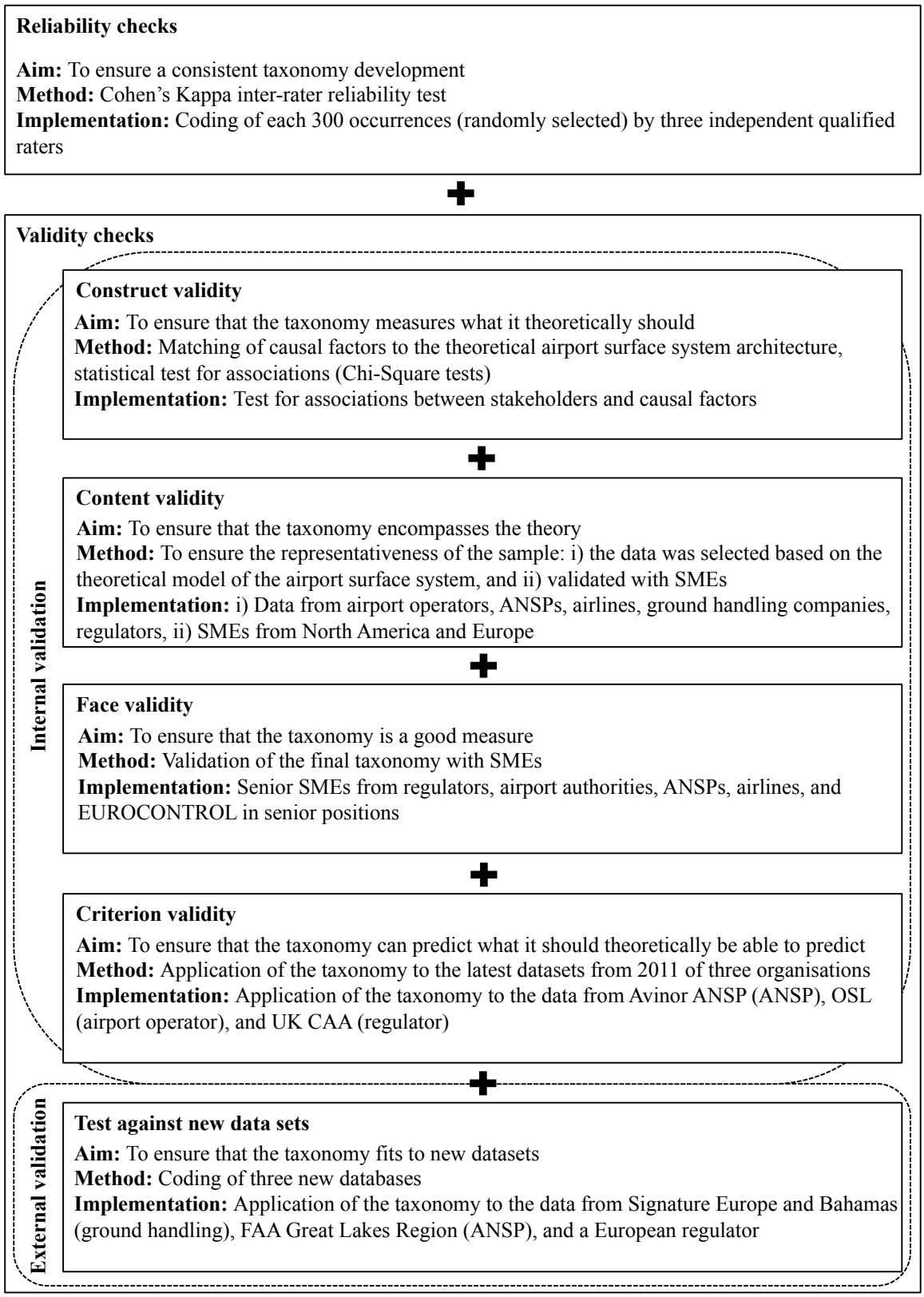


Figure 107: Methodology of taxonomy validation

9.2.2 Validation and Reliability Checks

9.2.2.1 Reliability

To ensure the reliability of data coding three independent raters were each asked to code 300 occurrences at the first three levels of the taxonomy. Figures 108 to 110 show the results for Cohen's Kappa intra-rater reliability (κ) as well as the agreement rates between each pair of raters (i.e. independent rater vs. researcher). The results indicate that the coding of causal factors was reliable and consistent at all stages of the analysis (κ > .70).

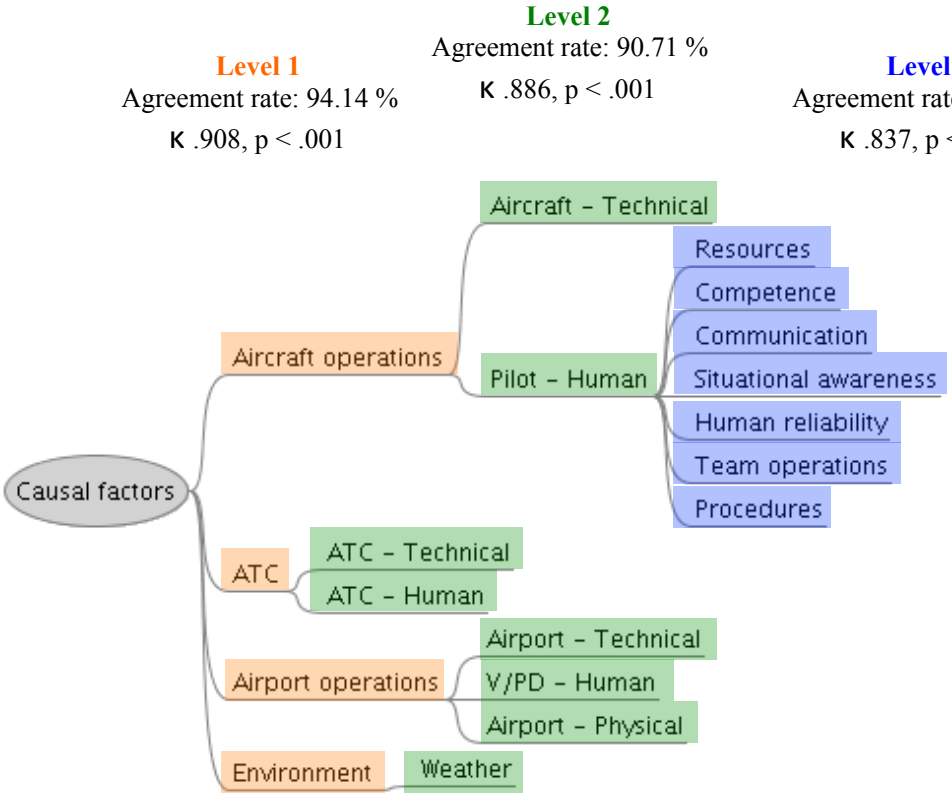


Figure 108: Reliability checks UK CAA

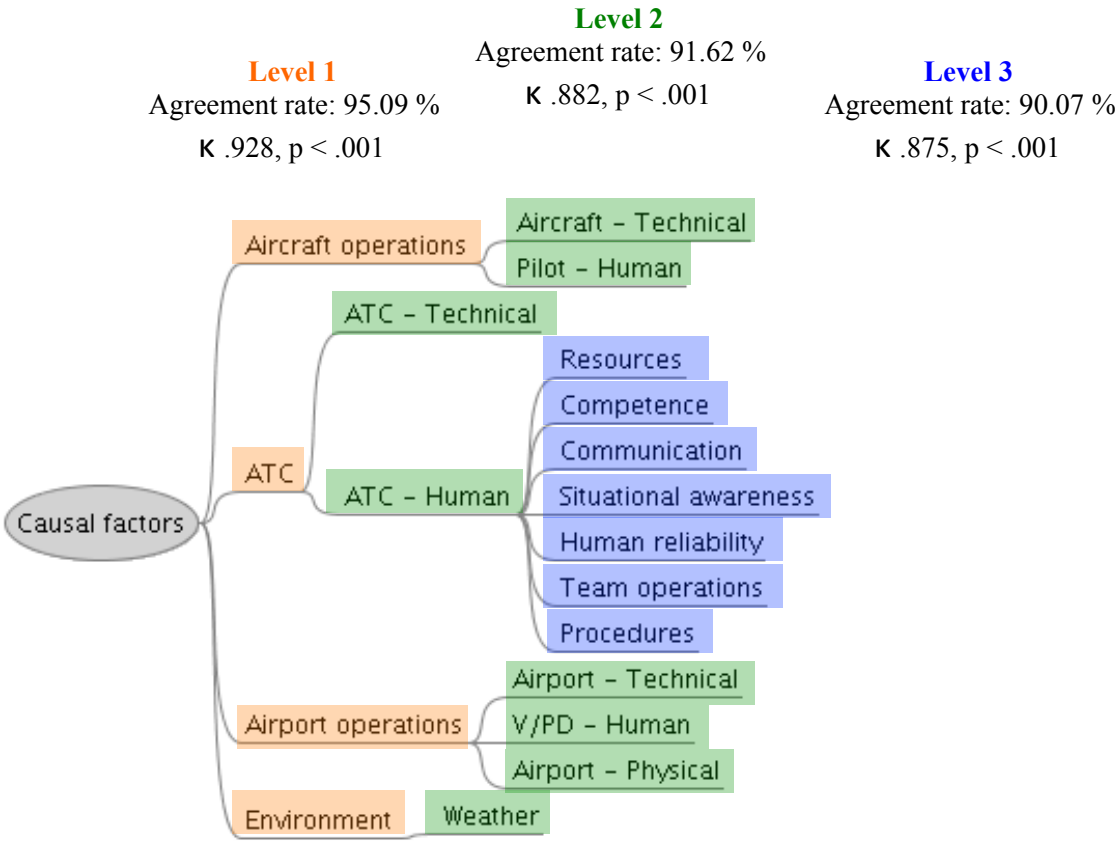


Figure 109: Reliability checks U.S. Western-Pacific Region

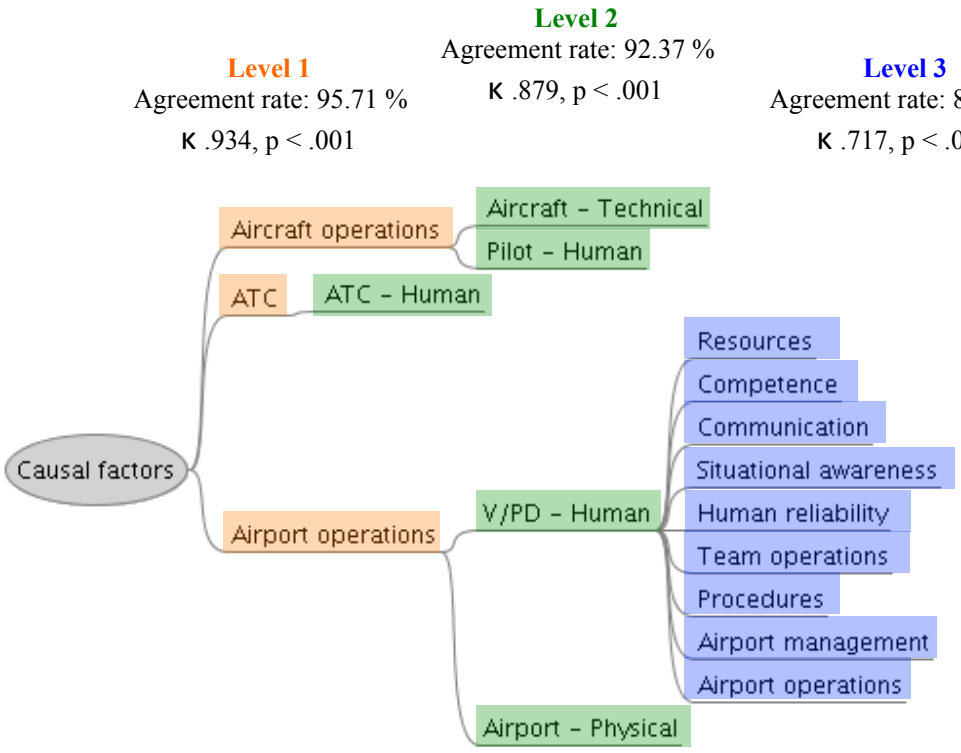


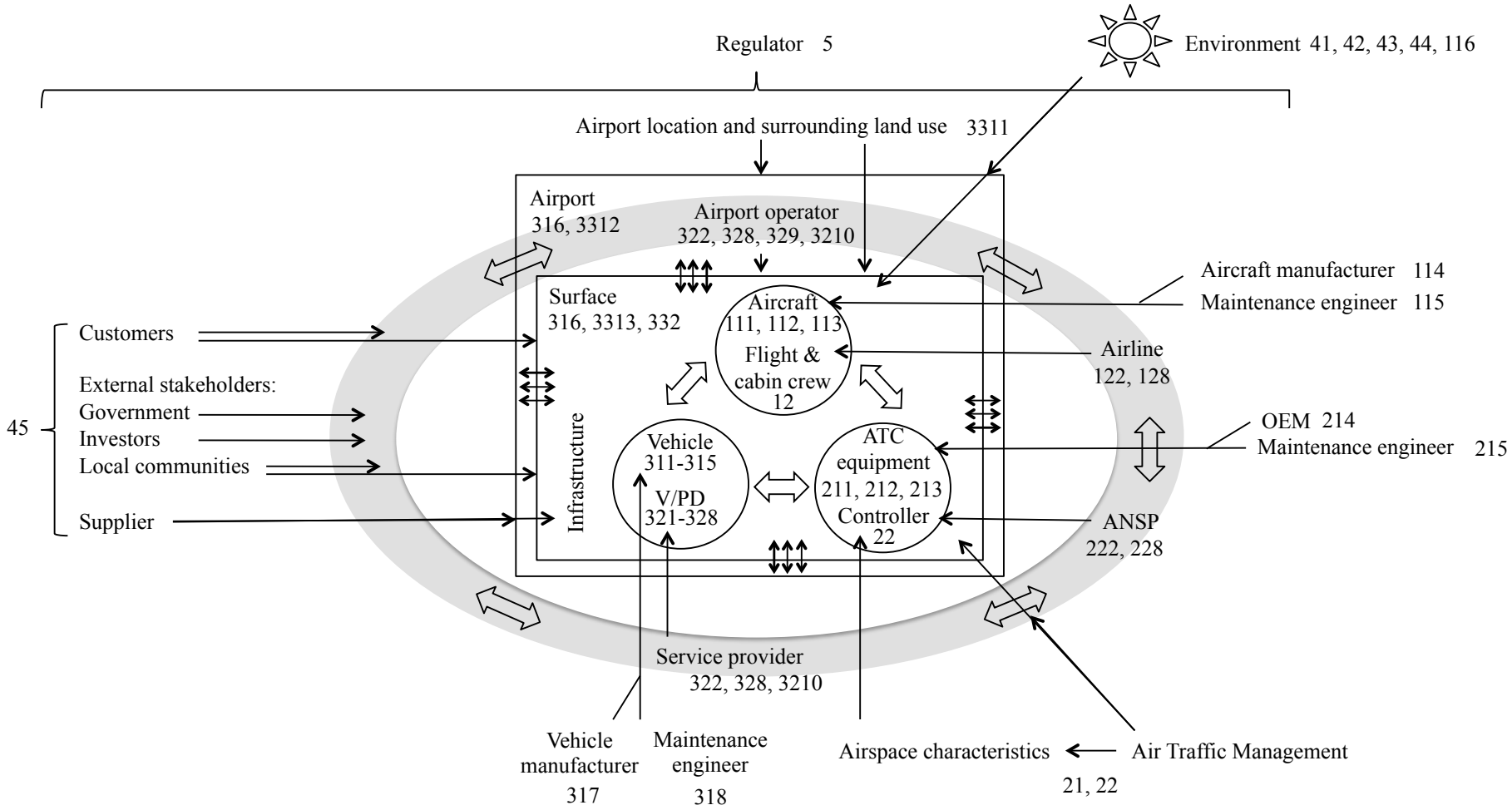
Figure 110: Reliability checks U.S. Northeast region

9.2.2.2 Construct Validity

After evaluating the reliability of the analysis, the taxonomy was checked for its validity. Matching the taxonomy to the airport surface system ensured construct validity. Figure 111 shows that the taxonomy does indeed capture the airport surface system in all its aspects. The analysis in Chapter 7 also revealed an association between stakeholders and causal factors (X^2 (15) = 1315.527, p < .001), which further supports the theory that every system component can fail.

9.2.2.3 Content Validity

The validation with ten SMEs lead to minor amendments in the taxonomy structure. For example, aircraft technical failures were originally just listed as a generic item in the taxonomy. However, the Chief Pilot pointed out that they should be grouped according to aircraft components / systems.



The corresponding legend for the causal factor codes can be found in Appendix VI.

Figure 111: Construct validity

9.2.2.4 Criterion Validity

The 'predictive validity' of the taxonomy was checked by applying the template to the latest datasets of three stakeholders. 100 occurrence reports from each of the three stakeholders, Avinor ANSP, OSL, and the UK CAA, were analysed and coded using the new taxonomy. This led to two interesting cases. One report in the UK CAA database had 'V/PD driving on the airport surface without a driving licence' as the cause for an incursion. This cause has not been identified explicitly before, but can be coded as the competence-related cause 'no training'. Furthermore, the analysis identified a new FO on the airport surface, i.e. a Chinese lantern. Again, such an object has not been identified before. However, it can be coded as 'other FOD / debris on the runway'. Overall, the taxonomy proved to fit the data and to produce valid results.

9.2.2.5 External Validation

Finally, the taxonomy was checked for external validity by applying its structure to three new datasets as outlined in the methodology in section 9.2.1.2. No conflicting issues were identified and the taxonomy was evaluated as valid.

9.2.3 Taxonomy Structure

The final taxonomy, after data analysis, divides the causal factors into the five major categories of:

- Aircraft operations,
- Air Traffic Control,
- Airport operations,
- Environment, and
- Regulatory system.

The first three levels of the taxonomy's structure were presented in Chapter 6 section 6.8. In total, the taxonomy contains 745 factors at the lowest of nine levels, which are presented in Appendix VI.

9.2.4 Comparison to Existing Taxonomies

The new proposed taxonomy addresses the subject of airport surface safety on a global basis from the perspectives of all relevant stakeholders involved in surface safety occurrences. Through the incorporation of different research methods, the taxonomy is more robust than existing approaches, and is applicable for all types of accidents and incidents on the manoeuvring area.

As shown in section 9.2.2.5, the taxonomy has been tested against three new datasets, and compared to existing classification schemes. The superiority of the new taxonomy over existing approaches is highlighted by three examples where incursions were coded using the new taxonomy. In order to compare the results, the same incidents were coded according to the ICAO, and EUROCONTROL classification schemes. ICAO's Runway Incursion Causal Factor Identification Form (International Civil Aviation Organization, 2007) and EUROCONTROL's Risk Analysis Tool (RAT) (The European Organisation for the Safety of Air Navigation, 2011b) were applied, since both are designed for collision / incursion incidents. The data originated from the new European regulatory database and the analysed incident reports were full investigation reports. As introduced in section 9.2.1.2, five Mandatory Occurrence Reports (MORs) were available from this European regulator. All of them referred to incursions and the three scenarios presented here were chosen randomly. The reports included the event sequence, transcripts of interviews, audio transcripts, investigation findings and a summary of the causal and contributing factors identified by the investigators. The following paragraphs introduce the incident scenarios and compare the coding of the occurrences according to the three chosen classification schemes.

Scenario I:
An aircraft was instructed to hold short runway (RWY) at the category (CAT) III holding point during low visibility operations. It passed the CAT III stop bar and held short of RWY before the CAT I holding point.

Table 53: Coding occurrence I

Coding according to the new taxonomy	Coding according to ICAO	Coding according to EUROCONTROL
• Code 1: 'Correct readback, followed by an unauthorised manoeuvre' • Code 2: 'Pilot crossed stop bar in front of a runway' • Code 3: 'Pilot entering a runway without clearance'	• Code 1: 'Flight Crew entered the runway after being instructed to "hold short"'	• Code 1: 'Correct pilot readback followed by incorrect action'

The taxonomy developed throughout this thesis and the ICAO coding form capture the causal factor of 'pilot entering a runway without clearance'. However, the new developed taxonomy is able to describe the occurrence in more detail, highlighting that the pilot readback correctly, but still crossed a stop bar in front of a runway. This information cannot be gathered through the ICAO coding form. According to RAT the incident can be described as 'correct pilot readback followed by incorrect action'. A more detailed code that allows an understanding of what went wrong does not exist at an appropriate level.

Scenario II:
An aircraft was instructed to enter a taxiway (TWY) to hold short RWY. It passed the stop bar on TWY and held short of the Cat I hold.

Table 54: Coding occurrence II

Coding according to the new taxonomy	Coding according to ICAO	Coding according to EUROCONTROL
• Code 1: 'Correct readback, followed by an unauthorised manoeuvre' • Code 2: 'Pilot crossed stop bar on a taxiway'	• No mapping existing in ICAO	• Code 1: 'Correct pilot readback followed by incorrect action'

The same conclusions as for the first incident can be drawn for the new taxonomy and the RAT classification scheme. As the ICAO Runway Incursion Causal Factor Identification Form fails to capture taxiway occurrences, the causal factors underlying this incident cannot be captured.

Scenario III:

An aircraft landed on RWY. As the aircraft completed its roll to join TWY, the pilot informed the tower that he had seen ground equipment at the runway edge lights on the right hand side. Maintenance vehicle X had been managing approved grass cutting operations at the time and had been instructed to vacate the flight strip. Maintenance vehicle X had informed the tower that all equipment under his supervision was clear of the flight strip.

Table 55: Coding occurrence III

Coding according to the new taxonomy	Coding according to ICAO	Coding according to EUROCONTROL
• Code 1: 'Authorised airfield escort did not ensure that all vehicles under his supervision had vacated the runway when confirmation of vacation to the tower was issued' Contributing factors: • Code 2: 'Runway not visible to ATC' • Code 3: 'Vehicle – absence of beacon' • Code 4: 'Inconsistent radar signal'	• Code 1: 'ATC has limited view of the manoeuvring area'	• Code 1: 'Surveillance'

In this third instance, the new taxonomy captures all the causal factors identified in the investigation findings. The application of the ICAO coding form fails. The first code, whereby the authorised airfield escort did not ensure that all vehicles vacated the runway, could be captured under vehicle driver 'situational awareness' or 'clearances and instructions'. However, in order to code this, further information is needed on why the airfield escort failed to vacate the runway. The investigation could not bring this information to light. In addition, the ICAO coding form fails to capture generic technical problems. The RAT taxonomy also fails to capture the incident. RAT does not account for airport operations-related factors, such as vehicle driver issues.

It can be concluded that a taxonomy has to be designed for a specific purpose and requires the right amount of detail. ICAO does not capture taxiway events. This is important since incidents happen on taxiways just as much as on runways. Indeed, collisions on the manoeuvring area, for example, are the highest accident category in the aviation system for the European Civil Aviation Conference (ECAC) member states (The

European Organisation for the Safety of Air Navigation Safety Regulation Commission, 2010). In addition, the ICAO Coding Form was inadequate in capturing all causal factors underlying the three analysed examples. The RAT taxonomy, on the other hand, seems to capture the description of an occurrence at too high a level. In addition, it is developed from an ATM perspective focusing on pilot and ATC-related factors as well as, to a large extent, on technical problems.

9.2.5 Application, Transferability and Limitations

In the context of SMS, the developed taxonomy can support the safety risk management process, in particular the data analysis function. The taxonomy provides a robust basis for safety data coding and subsequent data analysis. Both are fundamental to effective safety performance monitoring (safety assurance component). An example of the limitations experienced by one of the safety data providers (referred to as company A) highlights the importance of having a robust taxonomy underpinning a safety data analysis process.

When company A receives a safety report, descriptors (occurrence type and what happened) are assigned to the occurrence. Based on these descriptors appropriate investigators are assigned. Company A currently experiences the problem not having a robust taxonomy and that the descriptors evolved over time. This led to a very unsystematic classification system with multiple descriptors describing the same causal factors, others not in use or forgotten, and no explicit definitions. The safety analysts assign these descriptors based on ‘what they think these are’. Company A is currently putting a large effort into revising their system, starting with defining safety occurrences and ‘cleaning up’ their classification system. A robust taxonomy with a clear structure would have prevented such a situation.

Similar feedback has been received from the FAA in the U.S., where the data analysts pointed out that the lack of integrated taxonomies is one of the major problems the organisation currently faces. Each department keeps its own data (e.g. data for different occurrence types are kept in different databases) and uses its own taxonomies. These taxonomies have been developed individually and are not integrated. Consequently, the various departments within the FAA cannot communicate effectively with each other.

Indeed, the data analysts stressed that the FAA is in desperate need of good taxonomies (Structured communication with FAA Runway Safety Office Analysts, August 2011).

The taxonomy has been developed using a hybrid-methodology that is flexible and can be applied to other parts of the airport system, as well as other areas of research. For example, there is currently no integrated taxonomy for ground handling, with each operator being responsible for its own handling of safety. Therefore, safety assessments for ramp operations would also benefit from a holistic taxonomy. This flexibility also makes it easier to develop the taxonomy further if needed. This is important, for example, in the context of a developing ATM system and ATM upgrade initiatives such as the Single European Sky ATM Research (SESAR) and the Next Generation Air Transport System (NextGen) in the U.S. Both SESAR and NextGen are working on the development of a technological and operational transformation of the ATM system to meet future airspace capacity and safety needs (e.g. The European Organisation for the Safety of Air Navigation, 2013). Changing concepts in respect to operations might introduce new failures to the airport surface system and these can be easily incorporated into the developed taxonomy.

The taxonomy has been developed with the aim of providing a tool that supports the analysis of safety data (i.e. coding). It is limited by not taking organisational factors (e.g. organisational climate, processes, resource management), and detailed regulatory impacts into account. These factors cannot be extracted from occurrence reports and, therefore, could not be identified through the research methods applied in this thesis. Although the new taxonomy is not all encompassing, it provides a robust tool for the analysis of safety data.

9.3 Macroscopic Scenario Tool

Finally, the system and system failures were matched resulting in a model of airport surface operations that allows for the identification of the key drivers of airport surface accidents and incidents. The following section presents the details of the model and discusses its application in the context of a SMS.

9.3.1 Introduction of the Tool

Figure 116 shows the final airport surface system architecture. The stakeholders are highlighted in blue font and infrastructure in green. Associated with the stakeholders and infrastructure, denoted through black numbers, are the failures that can challenge the safety of operations. Blue arrows represent the interactions between stakeholders and red arrows the stochastic elements. How each of the components and interactions can challenge the safety of the system is discussed in the following paragraphs.

9.3.1.1 Direct Drivers

Chapter 5 noted that the factors causing accidents / incidents are typically identified for specific occurrence types from the perspective of a single stakeholder. With the airport surface system architecture proposed here it is now possible to show all the drivers of airport surface safety occurrences integrated for all relevant stakeholders. These include direct and indirect drivers as follows:

Direct drivers: factors that directly challenge the safety of the operation / tasks of a stakeholder (Actor A).

The following example clarifies the concept of direct drivers. The occurrences presented in this section for illustrative purposes are extracted from the safety databases used in this thesis. The aircraft and vehicle identifiers were removed and replaced by a/c, and V/PD, respectively.

Example I:
"An a/c 1 ready for departure was instructed to hold short of Runway 15. The a/c 1 pilot read back hold short correctly. Subsequently the a/c 1 was observed holding between the hold line and runway edge line at approach end without clearance. No conflicts were reported. The a/c 1 was then cleared for take-off."

In this example, an error occurred in the task sequence of the pilot's operation. The pilot was instructed to hold short, and read back correctly. However, the plane crossed the

hold line. The deviation from the normal operation was caused by the pilot (Actor A). Figure 112 shows this deviation graphically.

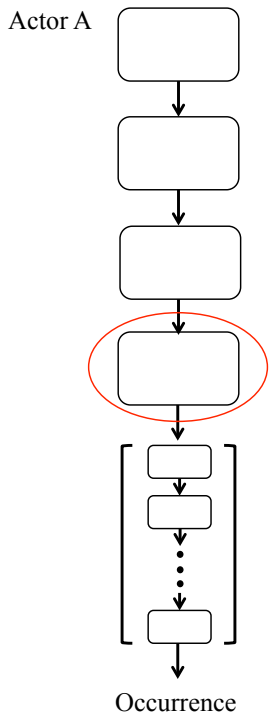


Figure 112: Direct drivers

Figure 112 shows the task sequence of Actor A. The red circle highlights the task within the sequence that failed leading to an occurrence. In Example I the pilot failed to hold short, which resulted in a runway incursion. The failure can lead directly to an occurrence, as seen in Example I. However, it is also possible that a failure within the task sequence leads to an occurrence only after several other tasks have been completed. In the airport surface system architecture, direct drivers are assigned to the corresponding stakeholder / components through the numbers in black.

9.3.1.2 Indirect Drivers

Indirect drivers: factors that do not directly challenge the safety of the operation / tasks of a stakeholder (Actor A), but can become critical for this stakeholder over either one of the two specified interfaces.

a) *Factors that become critical for a stakeholder's operation over the interface of communication.*

Example II:

"An a/c 1 was cleared for take-off on Runway 34R full length. A/c 2 was issued taxi into position and hold (TIPH) on Runway 34R after the a/c 1 started take-off. When the a/c 1 was more than 6,000 feet from the threshold, Local Control (LC) issued take-off clearance to the a/c 2. The a/c 2 started take-off roll when the a/c 1 was 7,400 down the runway. The

a/c 1 pilot reported an aborted take-off and the a/c 2 take-off clearance was cancelled. The a/c 2 rolled approximately 600 feet before exiting Runway 34R. Closest proximity reported was 7,400 feet horizontal."

In this example, ATC misjudges the distance between two aircraft and clears a/c 2 for take-off, although a/c 1 was still on the runway. The result was a loss of separation on the runway. Figure 113 highlights how indirect drivers can influence the operations / tasks of different stakeholders one another. The important factor to note is that both actors, a/c 2 and ATC, are in contact with each other over the interface of communication.

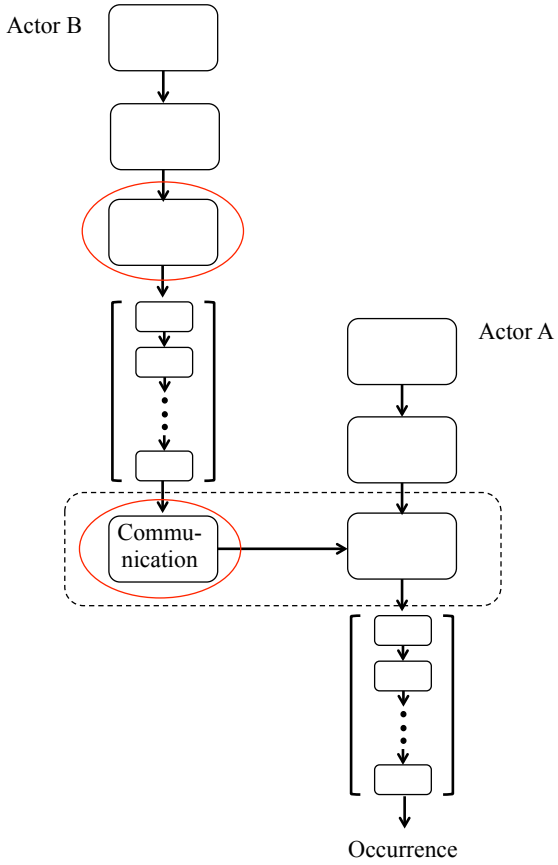


Figure 113: Indirect drivers – interface communication

In Example II the deviation (misjudgement of distance between two aircraft) occurred during the execution of ATC's tasks (Actor B). ATC communicated the take-off clearance to a/c 2 (Actor A), who started its take-off roll. Here, the deviation was caused by ATC (Actor B) and influenced a/c 2 (Actor A) over the interface of communication.

The deviation within the operations of an Actor B can take on two forms (highlighted in red circles). The deviation can either occur within the task sequence (e.g. misjudgement of distances) and is later communicated, or can be an error in the communication itself (e.g. error in the message itself).

Note that Chapter 3 specified ATC's operation as a multi-tasking operation that does not follow a prescribed order of tasks. In order to simplify Figure 113 and the concept of indirect drivers, Actor B's tasks are represented as a task sequence. The blue lines in the final system architecture (Figure 116) describe the interactions between the stakeholders. The direction of the arrow denotes the direction of the influence. Any interaction can

involve some form of communication and, therefore, all stakeholders connected by blue lines can influence each other over the interface of communication.

b) Factors that become critical for one stakeholder's operation over the stochastic interface of location.

Example III:
"Two V/PD crossed Taxiway Alpha without clearance and without contacting ATC. The vehicles crossed in front of a taxiing a/c 1 by an estimated 75-100 feet."

Example III shows an occurrence where a third party (Actor C), that was not in contact with the a/c 1 (Actor A) influenced its operations. In this example, the deviation occurred within the task sequence of the vehicle drivers (Actor C). The vehicle did not contact ATC and infringed onto the taxiway, which impacted on the operations of an aircraft a/c 1 (Actor A) that was in the same location. Figure 114 gives a graphical example.

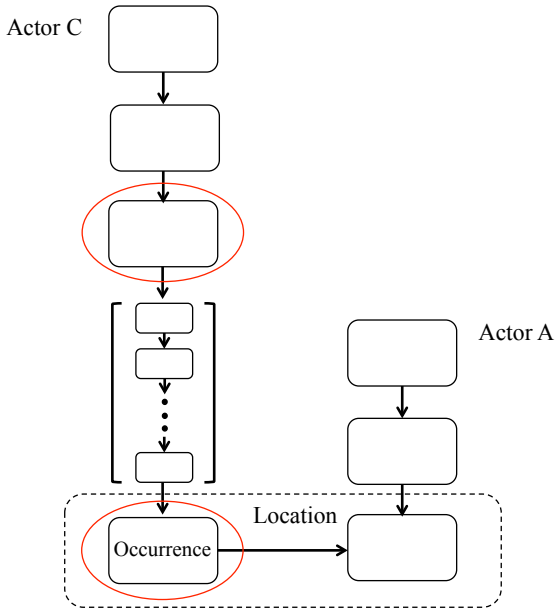


Figure 114: Indirect drivers - interface location

The deviation within the operation / tasks of an Actor C can take on two forms (highlighted in red circles). The deviation can either occur within the task sequence of Actor C leading to an infringement of location later on (e.g. no initial contact to ATC was established, followed by an infringement onto the surface), or can be the infringement itself (e.g. V/PD was instructed to hold short, he / she read back the instructions correctly, but crossed the hold line).

Figure 116 shows all actors involved in surface operations in blue font. These stakeholders can influence each other over the interface of location. The movements of

stakeholders during normal surface operations and associated locations have been defined in Chapter 3 during the task analysis of each actors' operation.

9.3.1.3 Stochastic Drivers

Another form of indirect driver is a stochastic driver.

Stochastic drivers: Stochastic factors that do not directly challenge the safety of the operation / tasks of a stakeholder (Actor A), but can become critical for this stakeholder over the interface of location.

Example IV:

"Pilot of an a/c 1, after landing Runway 17C and exiting at K8, advised Ground Control (GC) that a passenger had forced open a cabin door, exited the aircraft and was walking across the ramp from Runway 17R at K8 towards the terminal. The a/c 1 had just crossed 17R at K8 westbound and stopped with part of aircraft on 17R. ATCT immediately closed 17R. Individual was apprehended. No conflicts reported."

The data analysis in Chapter 8 (section 8.4) showed a stochastic influence of customers / passengers on surface operations and the above example highlights such an influence, i.e. a case whereby a passenger infringes onto the airport surface. This infringement can influence the operations of all other stakeholders in the same location on the manoeuvring area. Figure 115 summarises the case of stochastic drivers graphically.

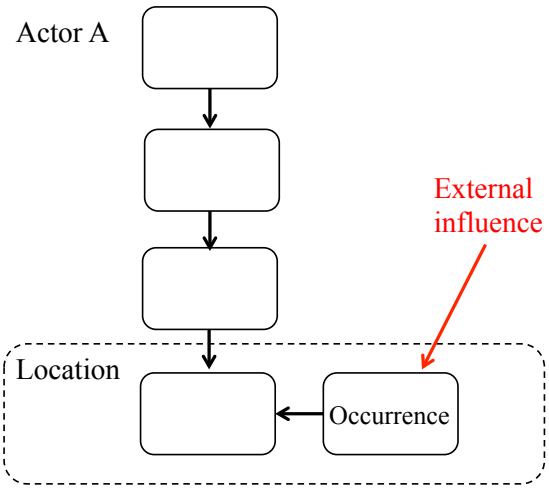
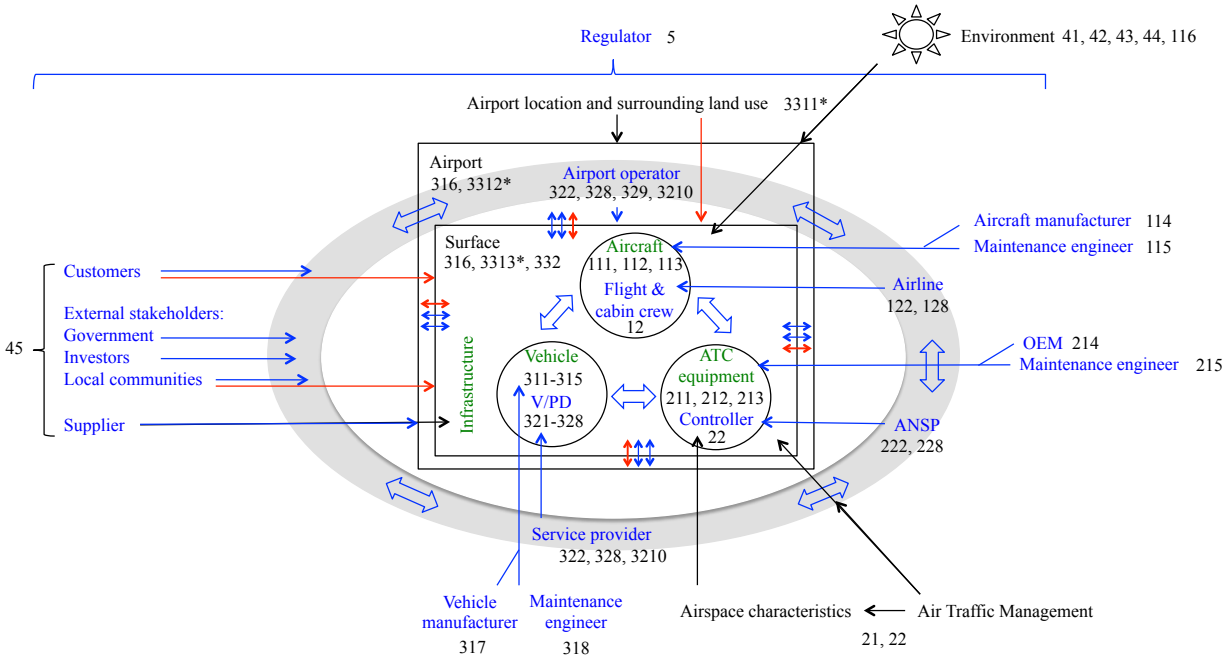


Figure 115: Stochastic drivers

In this example, the deviation is a stochastic factor, which causes an occurrence. The factor is critical for the operations of other stakeholders (e.g. Actor A) over the interface of the location (i.e. infringement). Stochastic factors are highlighted through red arrows in the airport surface system architecture and can influence all stakeholders that act upon the airport surface.

9.3.1.4 Other Drivers

In addition to direct and indirect drivers, the airport infrastructure (e.g. surface infrastructure, aircrafts, vehicles) can fail. The infrastructure is represented by green font in the airport surface system architecture (Figure 116). Infrastructural failures can influence other stakeholders over the interface of location (e.g. inadequate marking, signage, lighting on a taxiway can influence the operations of pilots and V/PD on that taxiway). Furthermore, other non-stochastic external factors such as weather have an influence on airport surface operations. Figure 116 highlights them in black font. Often, these drivers do not occur in isolation, but as a combination.



Legend:

1 Aircraft operations
- *11 Aircraft – Technical*
  - 111 Aircraft technical failure
  - 112 Aircraft weight and balance
  - 113 Master caution warning
  - 114 Aircraft design / manufacturing
  - 115 Aircraft improper maintenance
  - 116 Environmental influences
  - 117 Other
- *12 Pilot – Human*
  - 121 Resources
  - 122 Competence
  - 123 Communications
  - 124 Situational awareness
  - 125 Human-machine interface
  - 126 Human reliability
  - 127 Team operations
  - 128 Procedures

2 ATC
- *21 ATC – Technical*
  - 211 Surveillance system
  - 212 Navigation system
  - 213 Communication system
  - 214 Equipment design / manufacturing
  - 215 Equipment improper maintenance
  - 216 Other
- *22 ATC – Human*
  - 221 Resources
  - 222 Competence
  - 223 Communications
  - 224 Situational awareness
  - 225 Human-machine interface
  - 226 Human reliability
  - 227 Team operations
  - 228 Procedures

3 Airport operations
- *31 Airport – Technical*
  - 311 Vehicle technical failure
  - 312 Radio communications
  - 313 Absence of radar beacon
  - 314 Ground handling equipment
  - 315 Tugs
  - 316 Airport meteorological equipment
  - 317 Vehicle / equipment design / manufacturing
  - 318 Vehicle / equipment improper maintenance
  - 319 Other
- *32 V/PD – Human*
  - 321 Resources
  - 322 Competence
  - 323 Communications
  - 324 Situational awareness
  - 325 Human-machine interface
  - 326 Human reliability
  - 327 Team operations
  - 328 Procedures
  - 329 Airport management
  - 3210 Airport operations
- *33 Airport – Physical*
  - 331 Design
  - 332 Surface infrastructure and conditions

4 Environment
- *41 Weather*
- *42 Geological disturbances*
- *43 Nighttime operations*
- *44 Wildlife*
- *45 External factors*

5 Regulatory system
- *51 Regulations not existent*
- *52 Regulations inadequate*
- *53 Regulations existent, nut not implemented*

* The factors 3311, 3312, and 3313 refer to airport location and surrounding land use, airport landscaping, and manoeuvring area design, respectively.

Figure 116: Macroscopic scenario tool

9.3.2 Application of the Tool

The developed model can be used 1) as a training and awareness tool to support the safety promotion component of a SMS, and ii) as a macroscopic scenario tool in the context of SMS change management.

The developed model provides a holistic overview of all the stakeholders involved in surface operations and enables a detailed understanding of the system failures, i.e. factors that cause occurrences, and how these can spread throughout the system. This has implications for risk mitigation measures, such as the design of training programmes. For example, while a pilot does not need to understand the causes of failures in the operations of other stakeholders in detail, he / she needs to be aware of them to the extent that they can impact his / her own operations. Training programmes need to account for this in order to allow every stakeholder to develop an understanding of what the other actors are doing around them and how that can impact their own operations. In addition, a holistic understanding of operational practices on the airport surface, and associated hazards, improves the situational awareness of all stakeholders, which is one of the most frequently cited causes e.g. for incursions (Airbus, 2004c; Federal Aviation Administration, 2008b; International Civil Aviation Organization, 2007). Overall, the developed airport surface system architecture is applicable to all stakeholders and helps practitioners to think 'outside the box', that is, to identify drivers that are not directly related to an operator's activities, but may indirectly influence their operations and safety. It is recommended as a training and awareness tool and, therefore, it supports the training and education, as well as the safety communication functions, of the safety promotion component of a SMS.

Aviation is a fast moving environment and the service providers experience permanent change which requires the adjustment of safety risk controls in the operational environment (International Civil Aviation Organization, 2009e). Therefore, the model is also recommended as a macroscopic scenario tool for use in SMS change management, thus supporting the safety assurance component of a SMS. Its role in supporting change management is illustrated in Figure 117, which shows the scenarios and changes that need to be considered when building a new runway. The change in the system (i.e. the build of the runway) is shown in green and its system-wide impacts highlighted in red.

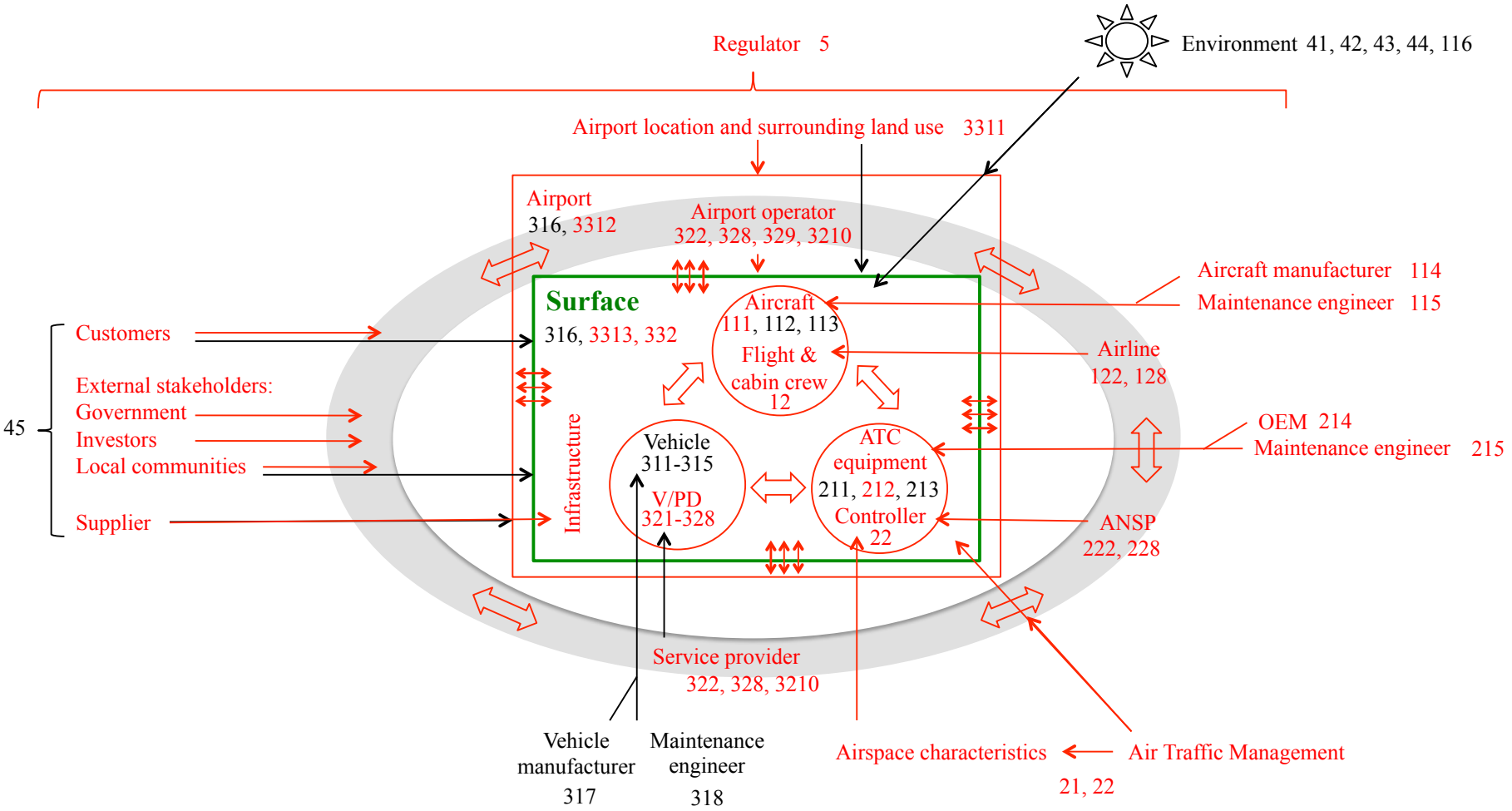


Figure 117: Scenario evaluation new runway

The building of a new runway is a complex decision not only for the airport, but also for the whole system. A new runway would change the manoeuvring area design and its associated infrastructure (e.g. visual and electronic NAVAIDs). In addition, it has an impact on the operations of pilots, V/PD and ATC. Associated with this are possible changes in the training programmes and operating procedures of the corresponding service providers (e.g. airlines, ANSPs, airport operators). In the case of the airport authority a new runway would also require the maintenance of this new piece of infrastructure, which influences, e.g., surface inspections and snow removal activities and may even require the acquisition of new equipment to accommodate these operations. Furthermore, a change in the layout would require the adjustment of, e.g., electronic moving map displays in the cockpit, which influences aircraft manufacturers and maintenance engineers that have to be trained on the technological changes. A change in the runway configuration also entails the change of Standard Instrument Departure Routes and Standard Arrival Routes (SIDs and STARs). Moreover, the building of a new runway needs to comply with area restrictions, address possible opposition from local communities, satisfy the interests of the government and investors, and comply with the regulatory framework. Therefore, the model developed here shows, on a macroscopic level, the impact of changes on the system and can therefore guide further analysis, for instance, which components should be simulated and analysed in further detail.

Similarly, a change in the components might also entail a change in the causal factors. For example, new factors may be needed, existing factors may need modification, or factors may need to be eliminated if they are no longer relevant. Since the model shows the causal factor groups associated to each component it can guide safety assessments that may be required by a change in the system.

9.4 Summary

This thesis has shown that the current airport SMS is more of a conceptual construct than a toolbox ready for implementation. This is justified by the absence of practical guidance on the development and implementation. This has been addressed in this chapter by the development of the tools required to support the safety risk management, safety assurance and safety promotion components of a SMS.

Firstly, the process model of airport surface operations to be used as baseline model for SMS has been finalised. Secondly, the chapter has combined the findings of the previous chapters in a new taxonomy of causal factors underlying airport surface safety occurrences and subsequently applied various checks to ensure its reliability and validity. The taxonomy has been developed using a new hybrid methodology that specifically targeted the limitations of previous research, resulting in a robust classification scheme which provides a better fit to airport surface safety data than existing templates. This was achieved through a holistic consideration of surface safety occurrences, a global focus, the combination of different research methods and data sources, and an integration of the different perspectives of aviation stakeholders involved in airport surface operations.

The new taxonomy provides a common industry language and state-of-the-art tool that supports the data analysis function in the context of SMS and, hence, provides a robust basis for data analysis. Its unique feature is its integration and applicability to all relevant aviation stakeholders in the context of surface safety. It is recommended for operational safety risk management for all aviation stakeholders.

Finally, a macroscopic scenario tool of airport surface operations was developed. Examples of its application for SMS change management (i.e. safety assurance component) and the training and education and safety communication functions (i.e. safety promotion) were demonstrated.

So far this thesis has addressed surface safety by modelling the airport surface system and identifying the possible failures in the process of surface operations. To identify those factors that are most critical for successful surface operations, the next two chapters quantify the system by proposing a structured framework for the analysis of causal factors.

10 The Impact of Airport Characteristics

The previous chapters have identified the causal factors underlying airport surface safety occurrences. Both, the literature review in Chapter 5 and the analysis of safety data in Chapters 7 and 8, have highlighted the importance of airport characteristics and their potential impact on airport surface accidents / incidents. For example, manoeuvring area geometry, or the inadequacy of airport surface infrastructure (e.g. signage) have been mentioned repeatedly for more than two decades as 'causal' for airport surface operations (Adam*, et al.*, 1992; Federal Aviation Administration, 2008b; International Civil Aviation Organization, 2007; National Transportation Safety Board, 1987). In spite of this, there is a lack of robust quantitative analyses in the literature and a relationship between airport characteristics and safety occurrences has never been proven. To lay the foundation for the seventh research objective (to propose a systematic framework to assess the functional relationship between accidents / incidents and their underlying causal factors), this chapter analyses the impact of airport characteristics on the occurrence of airport surface accidents and incidents.

Chapter 10 is split into four parts. The first presents the problem statement and justifies the need to analyse airport characteristics. The relevant data is collected by means of an airports survey, and the second part introduces the methodology, including sampling considerations and methods of data collection and data analysis. The data is then analysed for associations between airport characteristics and airport surface safety occurrences. The results are presented in part three and the implications of the findings in the context of SMS discussed. Finally, the chapter is concluded in the fourth part.

10.1 Background

Chapter 5 identified the factors in relation to airport characteristics that have the potential to impact the safety of surface operations. For example:

- A complex layout of the airport surface and its related infrastructure may cause a loss of pilot situational awareness, leading to an incursion (International Civil Aviation Organization, 2007; La Direction Générale de l'Aviation Civile, 2007; The European Organisation for the Safety of Air Navigation, *et al.*, 2011);
- The physical characteristics of runways, such as runway end safety areas, runway slope, runway condition (e.g. contamination), and surface operations and maintenance (e.g. snow and ice control and removal) might contribute to an excursion (Australian Transport Safety Bureau, 2008b; Flight Safety Foundation, 2009; Hall*, et al.*, 2008);
- Airport landscaping and surrounding land use may influence the presence of wildlife and is associated with the risk of a wildlife strike (Transport Canada, 2008; UK Civil Aviation Authority, 2008a), and;
- Surface infrastructure, operations and maintenance can lead to debris and eventually cause a FOD (Bachtel, 2010; Federal Aviation Administration, 2009a).

In addition, the analysis of safety data in Chapters 7 and 8 also identified airport characteristics (e.g. markings, signage, lighting) as having a potential impact on airport surface occurrences.

All these factors can be grouped under the topic of airport characteristics. However, although they are mentioned frequently as 'causal factors', there is a surprising lack of quantitative studies on the relationship between airport characteristics and surface safety occurrences.

A recent study by Galle, *et al.* (2010) analysed the impact of runway geometry on the rate of runway incursions. The authors clustered 80 airports from the U.S. Great Lakes Region into five clusters based on runway geometry. The study compared the rate of runway incursions across the clusters and found a similar median across the groups. The study concluded that runway geometry is not a significant predictor for runway incursions. Whilst this study provides an initial attempt of analysing the impact of airport characteristics on surface safety occurrences, it is limited in several respects. The authors consider runway geometry simply as one variable and do not elaborate on the particular geometric characteristics used for the clustering. However, it may be that only certain

geometric aspects are significant (e.g. number of runways, intersecting taxiways), and Galle, *et al.*'s study does not test for this. In addition, their study considers only runway geometry and ignores the operation of the runway. Furthermore, Galle, *et al*. focus on analysing the impact of airport geometric characteristics on the rate of runway incursions. While airport characteristics may not influence the rate of occurrences, they may impact on their severity, or their underlying causal factors, e.g. the type of human errors an airport is most likely to suffer. For example, specific airport characteristics may influence the occurrence of pilot, ATC, or V/PD-related factors.

This chapter analyses the impact of airport characteristics on the occurrence of airport surface accidents and incidents and their causes. In particular, airport characteristics are considered in eight distinct groups including: airport location, traffic characteristics, manoeuvring area geometry, equipment and installations, operations and maintenance, regulatory and human aspects. Based on the limitations of previous research, this chapter explores the associations between these airport characteristics and i) airport surface occurrence rates, ii) the severity of occurrences, and iii) the causal factors underlying occurrences.

10.2 Methodology

The impact of airport characteristics on the safety of surface operations is analysed in three steps. The methodology is presented in Figure 118.

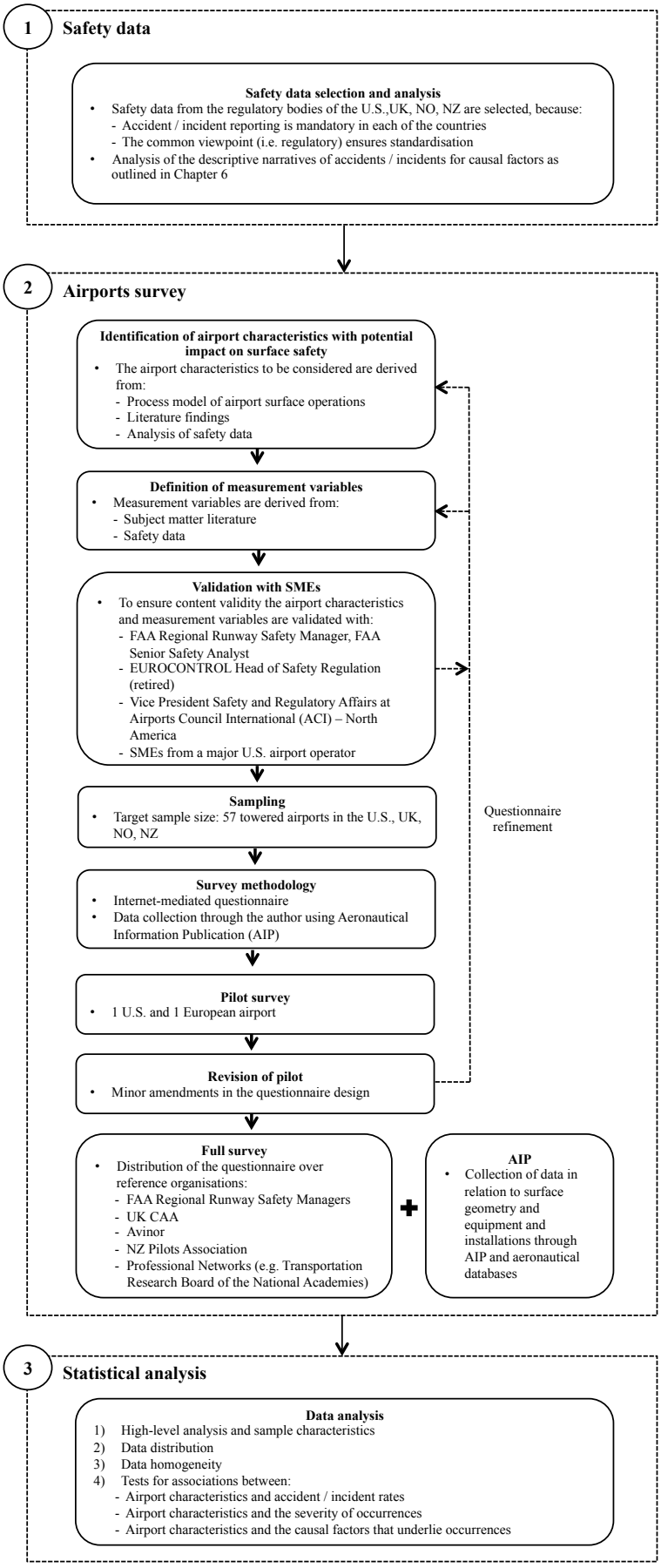


Figure 118: Methodology outline

10.2.1 Safety Data

Safety data from the regulatory authorities of the U.S., UK, NO, and NZ were used for this part of the research. Regulatory safety data was selected since the reporting of accidents and incidents is mandatory in each of the four targeted countries (e.g. UK Civil Aviation Authority Safety Regulation Group, 2011). Therefore, the selected databases should encompass all the reports made by the different aviation stakeholders (e.g. airline, ANSP, airport authority, regulator, handling companies). A common viewpoint, i.e. regulatory, ensures standardised data collection.

The data available for incursions, excursions and FOD were used. Wildlife strike data was excluded due to the inconsistent data collection mechanism together with the highly questionable quality of such data, as discussed in Chapters 5 and 6.

New Zealand CAA's database contains two spreadsheets (see data introduction Chapter 6 section 6.6.12). Due to resource and time constraints the previous chapters analysed only accidents / incidents that had been investigated. The second spreadsheet, containing occurrences that had not been investigated, was not considered. In order to make the current analysis comparable to the other countries, New Zealand's complete database is used for this part of the research, i.e. the analysis refers to all occurrences that happened at the airports considered in this chapter.

The data was coded to extract the causal factors following the methodology described in Chapter 6 section 6.7. The following section introduces the airport characteristics to be analysed.

10.2.2 Airport Characteristics and Measurement Variables

The airport characteristics were derived from the process model of normal airport surface operations, and were verified through the subject matter literature and findings from safety data analysis. The list of airport characteristics was subsequently validated with the following SMEs from the U.S. and Europe:

- A representative of a major U.S. airport authority (Deputy Director of Aviation Planning and Strategy),
- The Vice President of Safety and Regulatory Affairs from Airports Council International (ACI) – North America,

- The Regional Runway Safety Manager and a Senior Safety Analysts from the FAA,
- A former (retired) Head of Safety Regulation at EUROCONTROL.

To capture the airport operator's perspectives representatives of a U.S. airport authority and ACI, the global representative of the airports, were approached. As some of the airport characteristics (e.g. ILS) fall under the responsibility of the regulator and ANSP in the U.S., representatives of the FAA were consulted also. EUROCONTROL was approached to capture the European perspective. All SMEs were senior safety experts with a minimum of 15 years of relevant experience in aviation and airport operations as well as in safety. The airport characteristics were presented and the SMEs asked to systematically assess and comment on their validity (e.g. to assess whether the list in their opinion contained all relevant airport characteristics or missed important aspects). Table 56 shows the identified characteristics, classified into eight groups.

Table 56: Airport characteristics with potential impact on surface safety

Airport characteristics	**Process model (Chapter 3)**	**Literature findings (Chapter 5)**	**Analysis of safety data (Chapters 6-8)**
1. Airport location and surrounding land use	✓	✓	✓
• Airport location	✓	✓	✗
• Airport surrounding land use	✓	✓	✓
• Meteorological conditions	✓	✓	✓
2. Traffic characteristics	✗	✓	✗
3. Manoeuvring area physical characteristics	✓	✓	✓
• Manoeuvring area design	✓	✓	✓
• Landscaping	✗	✓	✗
4. Equipment and installations	✓	✓	✓
• Equipment status	✓	✓	✗
• Adequacy	✓	✓	✓
• Equipment failure (operational readiness)	✓	✗	✓
5. Visual navigation aids	✓	✓	✓
• Equipment status	✓	✓	✗
• Adequacy	✓	✓	✓
• Equipment failure (operational readiness)	✓	✗	✓
6. Manoeuvring area operations and maintenance	✓	✓	✓
• Manoeuvring area inspection	✓	✓	✓
• Surface conditions - adequacy	✓	✓	✓
• Infrastructure maintenance	✓	✓	✓
• Construction management	✓	✓	✓
• Vehicle management	✓	✓	✓
• Wildlife hazard management	✓	✓	✓
7. Regulations	✓	✓	✓
8. Human aspects	✓	✓	✓
• Level of training	✓	✓	✓

In a second step, measures for the airport characteristics introduced in Table 56 were derived. The measurement variables were derived from the subject matter literature and airport surface safety data. To ensure content validity, they have been validated with the senior safety experts from EUROCONTROL, the FAA, a major U.S. airport authority and ACI as outlined above. Table 57 contains the measurement variables and discusses how these potentially impact on airport surface safety. Some factors are highlighted as '*excluded*'. These are variables that could affect surface safety but which are not considered in this study for the following reasons:

- The airport characteristic is assumed to influence the level of wildlife, which is not considered in this thesis (e.g. airport surrounding land use);
- Data collection is expected to give unreliable results (e.g. meteorological conditions);
- Normal airport surface operations are assumed (e.g. the infrastructure is assumed to be in working conditions, failure rates are not considered);
- Runway / taxiway specific characteristics (e.g. type of ILS) are excluded, since safety data would have to be correlated to specific locations at airports. Such information is not consistently collected in the safety data.

Table 57: Measurement variables

Airport characteristics	**Measurement variables**	**Impact on safety**
1. Airport location and surrounding land use		
• Airport location	• Altitude (elevation in metres)	• Aircraft performance reduces at high altitudes
• Airport surrounding land use that causes disruption to aviation	*Excluded:* *- Airport surrounding land use possibly influences the level of wildlife strikes*	• Certain airport surrounding land uses influence the presence of wildlife (wildlife attractants)
• Meteorological conditions	*Excluded:* *- Any typical airport in North America and Europe will experience all meteorological conditions* *- Data collection (e.g. number of days certain meteorological conditions impact on normal surface operations) will lead to unreliable estimations*	• Weather influences operations and safety (e.g. snow / ice, fog, heavy storm, cross-winds)
2. Traffic characteristics		
• Traffic characteristics	• Number of movements per year • Peak number of operations during peak hours • Primary type of traffic handled at the airport • Number of airlines that have their home base at the airport	• Traffic volume, in particular during peak hours, increases the potential of occurrences • High number of airlines increases coordination; low number of airlines ensures that all flight crews are trained equally
3. Manoeuvring area physical characteristics		
• Manoeuvring area design	• Number of runways (RWY) • Number of taxiways (TWY) • Number of conflict points: - (RWY / RWY) - (RWY / TWY) - (TWY / TWY)	• Airfield layout and complexity can lead to confusion
• Landscaping	*Excluded:* *- Airport landscaping possibly influences the level of wildlife strikes* *- Data collection would require site visits*	• Landscaping influences the presence of wildlife (wildlife attractants)
4. Equipment and installations		

• Equipment status	• Number of communication channels • Number of frequencies *Excluded:* *- Type of landing system, as this is runway / taxiway specific data*	• Number of communication channels and frequencies can lead to e.g. frequency confusion
• Adequacy	• Adequacy of equipment / installations to support the operations based upon them*	• Inadequate equipment can lead to safety challenging situations
• Equipment failure (operational readiness)	*Excluded:* *- Data collection (e.g. equipment failure rates) using e.g. a questionnaire will lead to unreliable estimations, equipment failure databases at the airport level would be needed* *- It is assumed that the infrastructure is in working conditions during normal operations*	• Infrastructure / equipment failure can lead to safety challenging situations
5. Visual navigation aids (markings, signage, lighting)		
• Equipment status	*Excluded:* *- This study considers certified airports, hence, visual navigation aids are assumed to be compliant to ICAO Annex 14*	• Inadequate infrastructure / equipment can lead to safety challenging situations
• Adequacy	• Adequacy of visual navigation aids to support the operations based upon them* • Number of reports / complaints about confusing visual navigation aids	
• Infrastructure / equipment failure (operational readiness)	*Excluded:* *- See 'Equipment and installations – equipment failure'*	• Infrastructure / equipment failure can lead to safety challenging situations
6. Manoeuvring area operations & maintenance		
• Operational scenario	• Use of runways as taxiways *Excluded:* *- Operational scenario (i.e. runway operational practice), as this is runway specific information*	• The use of runways as taxiways possibly increases the risk of an incursion
• Manoeuvring area inspection	• Number of runway condition checks per day	• The mmanoeuvring area not being in a working condition can challenge the safety of operations upon it • Maintenance / construction work imposes an additional risk as surfaces might be closed during these times, and external people might access the surface, etc.
• Surface conditions - adequacy		
• Infrastructure maintenance	• Frequency of maintenance / construction work taking place on the manoeuvring area	
• Construction management		
• Vehicle management	• Requirement for clearance for vehicle drivers	• Free-range policies can challenge safety as vehicle drivers are

	• Vehicle equipment with radio communication • Subcontractors working on the manoeuvring area	cleared to use the surface without coordination with ATC • Vehicles not equipped with radio communications impose a safety challenge • Subcontracting increases e.g. the level of coordination and supervision required
• Wildlife hazard management	*Excluded:* *- Existence of a wildlife hazard management plan*	• Presence of wildlife imposes a risk to surface operations
7. Regulations		
• Regulations	• Engagement in proactive safety assessments apart from regulatory requirements *Excluded:* *- Compliance with regulatory requirements: airports are audited regularly, hence, compliance is assumed*	• Regulatory compliance impacts on safety. Since all airports are required to be compliant, it is of particular interest whether they engage in proactive safety assessments
8. Human aspects		
• Level of training	• Adequacy of the staffing level for airside operations* • Adequacy of training for operational personnel* • Adequacy of training for subcontractors*	• The level of staffing and the adequacy of its training influence the safety of surface operations

Adequacy = fit for purpose as determined by airport operational personnel

10.2.3 Sampling

The relevant airport characteristics data, i.e. measurement variables, were collected using a survey methodology. The population of airports sampled in this survey comprised airports with diverse underlying characteristics including, for example, manoeuvring area design, equipment status and operational practices. This sample was designed to be representative of the measurement variables introduced in Table 57.

The survey focused on towered airports in the U.S., UK, NO and NZ, giving a population size of 616 airports (Airways, 2013; Avinor AS, 2011a; Federal Aviation Administration, 2008b; Structured communication with UK Civil Aviation Authority Aerodrome Standards Department, 2012). Any sample of airports should be representative of the population. However, the collection of the sample should also be manageable given the available resources. As guidance, the minimum sample size for any statistical analysis should be 20, as defined in previous Air Traffic Management (ATM) research (e.g. Subotic, 2007). Salant and Dillman (1994) propose a sample size of 57 for a population with 750 members to make estimates with an error of no more than +/- 10.0%, at the 95% confidence level. For a population of 500 members a sample of 55 is proposed. The target sample for this study was 57 responses, representing 9.3% of the population.

10.2.4 Survey Methodology

A survey is defined as "a general view, examination, or description of someone or something" (Oxford Dictionaries, 2013). Surveying is a popular research method used for exploratory studies that allows the collection of a large amount of data from a sizeable population and subsequent statistical analysis (Saunders*, et al.*, 2007).

The most popular method of surveying is the questionnaire; a technique that requires each participant to respond to the same set of pre-defined and ordered questions. The following sections discuss the choice between structured interviews, telephone, postal and internet-mediated survey techniques (Salant and Dillman, 1994; Saunders*, et al.*, 2007).

Within a structured interview the surveyor conducts the interview in person using a questionnaire. Similarly, surveys can be conducted using the telephone. In both cases a pre-defined questionnaire is used, from which the interviewer should not deviate. The use

of personal communication in both techniques ensures that the respondent is the person who was addressed initially. In addition, through direct contact, a high response rate can be achieved (50-70%). Both techniques also allow for open questions, in which the respondent can answer each question in their own way, and closed questions that provide a number of alternatives to choose from. Whereas questions used in a telephone survey should be designed to be simple and easy for the respondent to understand, structured interviews allow for more complicated questions, because the interviewer can explain the circumstances of the case. While these techniques are preferred for complex topics and in situations when respondents are not likely to react by mail, considerable resources are required. Structured interviews are time consuming and imply high organisational costs (e.g. travel, hospitality), especially for research projects targeting foreign countries. Resource and funding constraints also impact on the size of the sample that can be collected. Telephone-based surveys offer a quick turn-around, since the average length of an interview should not exceed 30 minutes. However, the associated costs must be taken into account.

In contrast to the two surveying techniques introduced above, in postal and internet-mediated surveys the questionnaires are answered without the interviewer being present. This allows for the possibility to collect a large and geographically dispersed sample. Both, open and closed questions can be asked, though the questions should not be too complex. Via email, the potential respondents for internet-mediated questionnaires can be addressed directly, which ensures a high confidence that the right person will respond. However, this is not the case for postal surveys. Internet-mediated surveys require the least resources since they have low financial implications and allow the targeting of a large sample within a short time period. Postal charges need to be considered for mail surveys. However, both techniques suffer from their low response rates, which vary between 11 and 30%. For Internet-mediated surveys, higher response rates are achieved if they are distributed via intranet or a reference organisation.

After careful consideration of the advantages and disadvantages of the different survey techniques, an internet-mediated technique was adopted based on the need to collect data from a sample of 57 airports with a geographical dispersion covering four countries. In addition, such a survey enabled the relevant airport personnel to be addressed directly.

There were considerations related to the collection of data on the physical characteristics of the manoeuvring area (e.g. the number of runways, taxiways, and intersections). Discussions with the Vice President of Safety and Regulatory Affairs at ACI

– North America, revealed considerable inconsistencies in the ways airports count these within any country, in addition to variations between countries (Structured communication with Vice President Safety and Regulatory Affairs Airports Council International - North America, 2011). To ensure a standardised and consistent form of data collection, the data was collected directly by the author using the aeronautical information publication (AIP), i.e. aeronautical charts. A similar decision was made for other publicly available information, i.e. airport equipment and installations. In addition, data collection by the author helped to control the length of the questionnaire. Hence, a combined approach of internet-mediated questionnaire survey and data collection using AIP and aeronautical databases was applied for data collection.

10.2.5 Questionnaire Design

The questionnaire design was based upon four design principles to account for the following:

1. Clarity of questions to avoid any ambiguity in the self-completion survey.
2. Definition of all key terms to ensure a common understanding on the part of all respondents.
3. An emphasis on 'closed questions', which allow the respondent to choose an answer from pre-defined choices. Open questions were only used to gather operational airport data (e.g. traffic characteristics).
4. Structure of the questionnaire around the main objective of the survey research. All the questions were designed to match those airport characteristics that have a potential impact on surface safety as defined in Table 56 and Table 57.

The questionnaire was validated with the same SMEs introduced in section 10.2.2. The questionnaire was presented and the SMEs asked to systematically assess and comment on the validity of questions. The questionnaire was refined over several iterations to only include essential questions that enabled meaningful statistical results, while still matching the process model. The final version covered a total of 18 airport characteristics and can be found in Appendix VII.

10.2.6 Pilot Survey

Prior to conducting the full survey, a small-scale pilot survey was conducted both to verify the clarity of the questions posed and to assess the time necessary to complete the questionnaire. One U.S. airport and one European airport were surveyed and the results used to refine the questionnaire design, e.g. rephrasing some of the questions for clarity.

10.2.7 Full Survey

The questionnaires were distributed to all the airports in the target population. This decision was based on the expected low response rate of internet-based surveys, i.e. 11-30% (Salant and Dillman, 1994; Saunders*, et al.*, 2007). The questionnaires were distributed over reference organisations in:

- The U.S. where the FAA Regional Runway Safety Managers distributed the survey;
- NZ where the New Zealand Airports Association assisted with the data collection, and;
- NO where the survey was distributed by Avinor, the Norwegian ANSP, an organisation that is also responsible for the operations of airports in the country.

In addition, professional networks (e.g. Transportation Research Board (TRB) of the National Academies) were exploited to gain more responses. The questionnaire was distributed to relevant personnel in senior positions in the operations departments of the airport authorities (e.g. Head of Airfield Operations). In the UK, the UK CAA provided the contact details of UK airport operations directors, who were subsequently contacted directly.

10.2.8 Aeronautical Information Publication and Aeronautical Databases

Data on the physical characteristics of the manoeuvring area, as well as equipment and installations was collected using two sources of publically available information:

1. Aeronautical charts to extract geometric characteristics of the manoeuvring area:
   - FAA digital – Terminal Procedure Publication (d-TPP) (Federal Aviation Administration National Aeronautical Charting Office, 2011);
   - Aeronautical Information Publication (AIP) New Zealand (Civil Aviation Authority of New Zealand, 2011);

- Aeronautical Information Publication Norway (Avinor AS, 2011a);
- European AIS Database (EAD) (The European Organisation for the Safety of Air Navigation, 2011a).

2. Aeronautical databases to collect information regarding airport equipment and installations status:
   - AirNav (AirNav.com, 2013);
   - Aircraft Owners and Pilots Association (AOPA) (Aircraft Owners and Pilots Association, 2013);
   - Airport-Data.com (Airport-Data.com, 2013);
   - World Aero Data (Worldaerodata.com, 2013).

AirNav and AOPA's airport directory both use information from official FAA publications, such as the Airport / Facility Directory, and present it in a more structured, presentable and easy to access manner. The AOPA airport directory, for example, is updated every 56 days in conjunction with the FAA update cycle (Aircraft Owners and Pilots Association, 2012). Hence, both databases can be evaluated as reliable. This was confirmed through structured communications with senior safety experts (Structured communication with Vice President Safety and Regulatory Affairs Airports Council International - North America, 2011). One disadvantage is that these two databases are limited to aeronautical information in the U.S.

In order to extract the relevant data for Europe and New Zealand two additional databases were identified, airport-data.com and World Aero Data. The former provides global data compiled from national databases (e.g. National Flight Data Centre (NFDC), FAA Air Traffic Airspace ATA-100 database). AirNav, AOPA, and airport-data.com have been compared regarding their data entries for U.S. airports and showed similar data entries. Thus, airport-data.com is evaluated as reliable source. World Aero Data obtains its information from the Digital Aeronautical Flight Information File (DAFIF), a set of files containing airport data for the entire world provided by the U.S. military. However, DAFIF was closed for public use in October 2006. Since World Aero Data is now seeking information from national databases, some of the information in the database might be out-dated. Thus, World Aero data was used only to determine information regarding communication devices in cases where airport-data.com lacked this information.

10.2.9 Potential Sources of Error

Two main sources of potential errors were identified in the assessment of the survey: respondent and data pre-processing errors. The former may occur due to two main reasons. The first is imprecision in the formulation of the questions and misinterpretation of the questions by the respondents. These aspects were addressed by both validating the questionnaire with SMEs and by the pilot study. Therefore, they should not have played a significant role in generating any such errors. Secondly, the knowledge of the respondent is critical. Questionnaire surveys face the challenge that they might be given to low-level staff who have inadequate experience and knowledge to answer the questions. This issue was addressed through the choice of data collection method and questionnaire design. Internet-based surveys offer the advantage of addressing the key personnel directly. The questionnaires were distributed directly to operational personnel in senior positions. In addition, the questionnaire was designed to be easy to answer for any airport operator. Any information that airport operators would not have pre-defined was excluded and collected by the author. Thus, lack of knowledge of the respondents should have played only a minor role in the data collection process.

The possibility of errors arising during data extraction from AIP and data pre-processing was mitigated by extra care during the data input stage (i.e. double checking of each input by an independent assessor).

10.2.10Data Analysis

After the relevant data had been collected, a master file matching the airport characteristics data with the corresponding safety data was created. It was subsequently analysed in four steps.

10.2.10.1 High-level Analysis and Sample Characteristics

First, descriptive statistics (e.g. frequency analysis, bar charts, boxplots) were used to understand the characteristics of the sample and to identify outliers (i.e. data points that are not consistent with the others within a sample from the same population).

10.2.10.2 Data Distribution

Following the identification of the data characteristics and detection of outliers the distributions of the data were analysed. The dataset contained four different data types, i.e.:

- Continuous data (e.g. normalised number of occurrences);
- Ordinal categorical data (e.g. severity of occurrences);
- Nominal categorical data with multiple categories (e.g. causal factors, use of runways as taxiways);
- Nominal categorical data with two categories (binary) (e.g. adequacy of equipment / installations on the manoeuvring area).

Using the Kolmogorov-Smirnov test (for samples > 50) and the Shapiro-Wilk test, (for samples < 50) the continuous data was tested for normality. These tests compare the distribution of a variable in the sample to a normally distributed set of scores. If the tests are not significant ($p > .05$), then the distribution of the sample is not significantly different from a normal distribution, i.e. the variable is normally distributed. However, if the test is significant ($p < .05$) then the distribution of the tested variable is significantly different from a normal distribution, i.e. it is non-normal (Field, 2009).

10.2.10.3 Data Homogeneity

The test for homogeneity is necessary to test whether the data collected from the four different countries originate from the same population and can be aggregated. The non-parametric Kruskal-Wallis (for continuous data) and Pearson Chi-Square (for categorical data) tests were applied. Kruskal-Wallis tests whether more than two independent groups of continuous data differ, and Pearson's Chi-Square tests the independence of two categorical variables. A significant test statistic ($p < .05$) indicates a significant difference between the tested groups, and such data should not be aggregated (Field, 2009).

10.2.10.4 Analysis for Associations

To analyse the relationships among the variables, the data was tested for associations as follows:

- Association between airport characteristics and occurrence rates,

- Association between airport characteristics and the severity of occurrences, and
- Association between airport characteristics and the causal factors that underlie occurrences.

Depending on the nature of the data and its distribution various statistical tests were applied, as detailed in Table 58.

Table 58: Statistical tests

Data type variable 1	**Data type variable 2**	**Normal distributed variables**	**Non-normal distributed variables**
Continuous	Continuous	Pearson's Correlation Coefficient (r)	Spearman's Correlation Coefficient (r_S)
Continuous	Ordinal categorical	-	Spearman's Correlation Coefficient (r_S)
Continuous	Nominal categorical - binary	Independent T-Test (t)	Mann-Whitney U Test (U)
Continuous	Nominal categorical - multiple categories	Analysis of variance (ANOVA)	Kruskal-Wallis (H)
Categorical	Categorical	Pearson Chi Square (X^2)	

The Pearson's correlation coefficient (r) for parametric data and Spearman's correlation coefficient (r_s) for non-parametric data are used to test the strength of relationship between two variables (see Chapter 6). The Pearson's correlation coefficient is computed by dividing the covariance of two variables (cov_{xy}) by the product of the standard deviation of these two variables ($s_x s_y$). With N as the total sample size, the test statistic is computed as:

$$r = \frac{cov_{xy}}{s_x s_y} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{(N-1) s_x s_y} \qquad (9)$$

where x_i and y_i are the observed values of a variable x, and y, respectively, $\bar{x}$ and $\bar{y}$ their mean values and s_x and s_y their standard deviations. N is the total sample size. Spearman's test works by ranking the data points in ascending order and then applying the parametric Pearson's correlation coefficient.

The independent t-test is a test that establishes whether two means collected from independent samples differ significantly, and therefore, it is used to test whether two independent groups differ. Its statistic is calculated as shown below, where n_1 and n_2 are the sizes of sample 1 and sample 2 respectively, $\bar{x}_1$ and $\bar{x}_2$ are the means of sample 1 and

sample 2 respectively, and s_p^2 is the pooled variance (i.e. the variance weighted by the size of sample on which it is based).

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_p^2}{n_1} + \frac{s_p^2}{n_2}}} \quad (10)$$

To test whether the means of more than two independent groups differ, the one-way independent ANOVA test can be applied. Its null hypothesis states that all groups are equal and the *F*-ratio is used to test whether this is true. The F-ratio is a measure of the ratio of the variation explained by the model MS_M (systematic variation) and the variation explained by extraneous factors MS_R (unsystematic variation) and is calculated as follows:

$$F = \frac{MS_M}{MS_R} \quad (11)$$

The null hypothesis (i.e. all groups are equal) can be accepted if the *F*-ratio is not significant ($p > .05$). On the other hand, if the *F*-ratio is significant ($p < .05$) then the null hypothesis can be rejected, which indicates that the means of the groups are significantly different.

The non-parametric equivalents of the independent t-test and ANOVA are the Mann-Whitney and Kruskal-Wallis tests. The Kruskal-Wallis procedure was introduced in Chapter 6. It tests the null hypothesis that the distributions of observations across *k* experimental conditions are the same. The Kruskal-Wallis procedure first ranks the observations and then sorts them into groups. Subsequently, the sum of ranks (R_i) and the number of observations n_i is obtained for each group. Once R_i and n_i have been calculated for each group, the test statistic, *H*, is computed as:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1) \quad (12)$$

The null hypothesis (i.e. observations are the same across groups) can be accepted if the test statistic is not significant ($p > .05$).

To test whether the distributions of observations across only two groups are the same, the non-parametric Mann-Whitney test can be applied. The Mann-Whitney test is

the non-parametric equivalent of the independent t-test. Similar to the Kruskal-Wallis procedure, the observations are ranked and grouped and then the sum of ranks (R_i) is calculated for each of the two groups. The test statistic, U, is calculated by the following equation:

$$U = n_1 n_2 + \frac{N_1(N_{1+1})}{2} - R_1 \quad (13)$$

where n_1 and n_2 are the sample sizes of groups 1 and 2 respectively, and R_1 is the sum of ranks for group 1.

To analyse interactions between two categorical variables the Pearson's Chi-Square test (X^2) is typically used. The test compares the actual frequencies observed in certain categories to the frequencies that might be expected in those categories by chance and can be calculated as follows:

$$X^2 = \sum \frac{(n_{ij} - \mu_{ij})^2}{\mu_{ij}} \quad (14)$$

where n_{ij} and μ_{ij} are the observed and expected frequencies, and i and j represent rows and columns in the contingency tables, respectively. The test requires that at least 80.0% of the cells in such tables have expected frequencies greater than five and that no single expected frequency is lower than one (Agresti, 2007; Field, 2009).

10.3 Results and Discussion

This section highlights the results of the analysis for associations. Firstly, a high-level analysis, i.e. frequency analysis, describes the characteristics of the sampled airports and safety data across the countries. Secondly, the distribution of the data and the appropriateness of the statistical tests are discussed, followed by a discussion on data homogeneity and its implications. Finally, statistical analysis allows for an in-depth investigation of the associations between airport characteristics and safety occurrences.

10.3.1 High-level Analysis and Sample Characteristics

A total of 58 airports responded to the survey, corresponding to a 9.4% response rate, slightly above the anticipated 9.3% to get a reliable sample. For sensitivity reasons, the airports are anonimised. Of the 58 responses, a major airport authority running five U.S. airports and a UK airport operator did not take part for sensitivity reasons. Overall, 52 airports completed the questionnaire. The distribution among the countries is as follows: 19 U.S., 14 UK, 16 NO, and 3 NZ.

The data represents a very diverse sample ranging from small airports with a low number of aircraft movements and a small number of runways and taxiway segments, to major airports with almost one million annual movements and highly complex layouts. This section introduces the characteristics of the sample further. It is organised in ten sections, corresponding to the eight classes of airport characteristics factors identified as having a possible impact on safety occurrences and a description of the safety data. For continuous variables the following are presented: the sample size (N), minimum (Min) and maximum (Max) value, the range, mean, and standard deviation (SD). In addition, the distribution of the data is indicated (i.e. normal (✓), non-normal (✗)). For categorical variables, the frequency distributions of the response categories are presented and discussed. This is followed by a discussion on outliers in the data. The data from the four countries is aggregated.

10.3.1.1 Safety Data

For incursions, the maximum number of normalised incursions is 162.11 per 100,000 movements. On the other hand, one airport did not report any incursion incident. This indicates that the number of incursions varies significantly between airports across different countries. The range of normalised excursions is 4.67 (per 100,000 movements) indicating that excursions are rare events at an airport with a mean of only 0.28 excursions (per 100,000 movements). The number of normalised FOD is slightly higher with a mean value of 2.34 (per 100,000 movements) and a range of 20.63 FOD incidents. The descriptives for the three considered occurrences types considered are summarised in Table 59.

Table 59: Descriptives - occurrence types

Variable	Data type	N	Min	Max	Range	Mean	SD	Normality
Normalised number of incursions	Continuous	52	0	162.11	162.11	11.95	25.94	✗
Normalised number of excursions	Continuous	52	0	4.67	4.67	0.28	0.74	✗
Normalised number of FOD	Continuous	52	0	20.63	20.63	2.34	5.01	✗

The severity classifications for occurrences differ across the countries. Table 60 shows the distribution of the severity levels of the U.S. RI database, which contains only incursions. Although the database collects both incursions on runways (i.e. runway incursion) and taxiways (i.e. surface incidents), severity assessments are only conducted for runway incursions, whereby one of five severity levels (Category (Cat) A to E[16]) is assigned to each occurrence. For this reason the analysis for associations between airport characteristics and severity can only take runway incursions into account (surface incidents were excluded from the analysis). In addition, the FAA changed its runway incursion definition and associated severity classification and adopted the ICAO's standard as of 1 October 2007 (Federal Aviation Administration, 2009c). The implication of this is that the severity classification before and after October 2007 differs. Consequently, any analysis in this chapter which refers to severity uses only a subset of the available data (i.e. runway incursions that occurred between 1 October 2007 and December 2009). During the time period considered there was almost an equal split between Cat D (48.6%) and Cat C (50.0%), whereas high-severity categories A and B occurred only four times (i.e. 1.4%).

[16] Runway Incursion Severity Classification:
Category A: A serious incident in which a collision was narrowly avoided;
Category B: An incident in which separation decreases and there is a significant potential for collision, which may result in a time critical corrective / evasive response to avoid a collision;
Category C: An incident characterised by ample time and / or distance to avoid a collision;
Category D: An incident that meets the definition of runway incursion such as incorrect presence of a single vehicle / person / aircraft on the protected area of a surface designated for the landing and take-off of aircraft but with no immediate safety consequences;
Category E: Insufficient information or inconclusive or conflicting evidence precludes a severity assessment (Federal Aviation Administration, 2010c)

Table 60: Severity classification U.S. runway incursions

Severity class	Percentage of runway incursions
A	0.4%
B	1.0%
C	50.0%
D	48.6%

Occurrences received through the UK CAA MOR scheme are also subject to an occurrence grading system, which is based on the severity of the occurrence and the likelihood of recurrence. The grading system uses five severity categories Cat A (severe), Cat B (high), Cat C (medium), Cat D (low), and Cat E (non-significant) (UK Civil Aviation Authority, 2011a). Table 61 shows the severity distribution of all UK occurrences. It can be seen from the table that the majority of occurrences are classified as low severity (i.e. 89.2%) and non-significant occurrences (Cat E) are in practice not captured in the database.

Table 61: Severity classification UK

Severity class	Percentage of excursions	Percentage of FOD	Percentage of incursions
A	0.3%	0.0%	0.0%
B	0.0%	0.0%	0.6%
C	1.8%	2.4%	5.7%
D	2.7%	7.8%	78.7%

Finally, the database provided by the CAA – Norway allowed only a distinction between accidents, serious incidents and incident, although no accidents were reported over the time period considered. In fact, 99.7% of occurrences were classified as incidents and therefore, no associations between airport characteristics and occurrence severity can be computed for Norway. Norway's severity classification for the collected data is presented in Table 62. Due to the low response rate of only three airports the severity classification of New Zealand has not been attempted.

Table 62: Severity classification NO

Severity class	Percentage of excursions	Percentage of FOD	Percentage of incursions / collisions
Serious incident	0.3%	0.0%	0.0%
Incident	1.4%	29.4%	69.9%

Of the extracted causal factors, a total of 60.8% were related to aircraft operations, 11.2% to ATC, 26.2% to airport operations, and 1.8% to environment / weather. Due to the low response rate in New Zealand, only the safety data from the U.S., UK and NO were analysed for their underlying causal factors. The distribution of causal factors per country is shown in Figure 119.

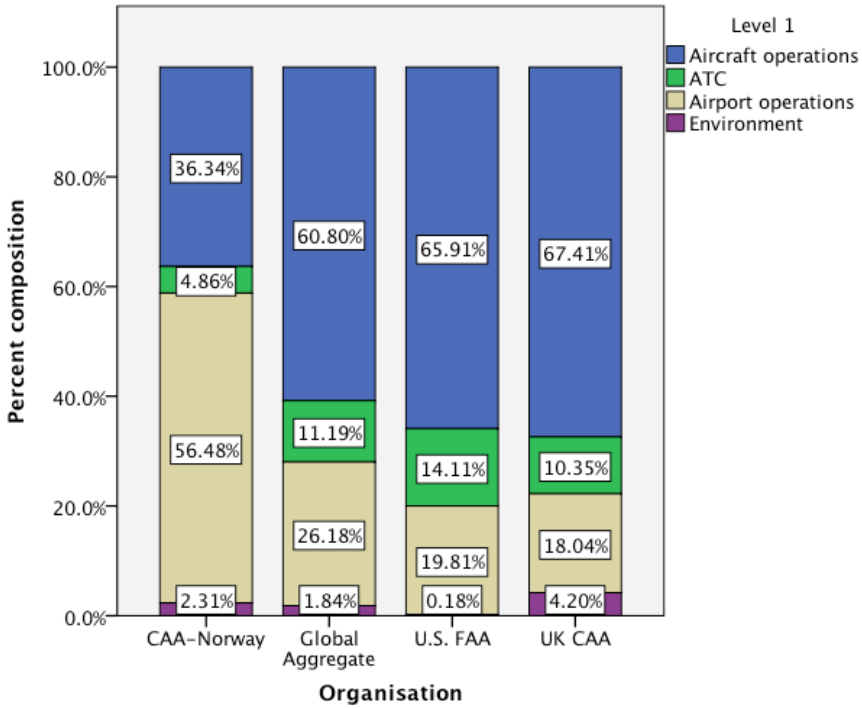


Figure 119: Distribution of causal factors

10.3.1.2 Airport Location

The altitudes of the airports range from just slightly above sea level (2.74 m) to a maximum of 1,288 m (Table 63). The altitude is a safety indicator, as aircraft performance reduces at high altitudes. In addition, the likelihood of poor weather conditions (e.g. wind conditions, fog) increases at high altitudes.

Table 63: Descriptives - airport location

Variable	Data type	N	Min	Max	Range	Mean	SD	Normality
Altitude (m)	Continuous	51	2.74	1,288.4	1,285.7	114.23	205.27	✗

10.3.1.3 Traffic Characteristics

Table 64 contains the details of the traffic characteristics of the sampled airports.

Table 64: Descriptives - traffic characteristics

Variable	Data type	N	Min	Max	Range	Mean	SD	Normality
Average number of movements per year	Continuous	52	3,084	979,360	976,276	199,481.43	234,265.35	✗
Peak number of operations during peak hours	Continuous	46	2	279	277	52.64	54.30	✗
Primary type of traffic handled at the airport	Nominal categorical	Unreliable data						
Number of airlines with home base at the airport	Continuous	Unreliable data						

The airports varied significantly in their traffic characteristics, from those with about 980,000 annual movements on average, to small airports with just over 3,000 annual movements. Similarly, the peak number of operations ranged from 2 to 279 at its maximum. The answers obtained for two questions from the survey were evaluated as unreliable and excluded from a further assessment (e.g. respondents chose multiple answers instead of only one). These two questions referred to the primary type of traffic and the number of airlines with home base at a particular airport.

10.3.1.4 Manoeuvring Area Characteristics

A total of 14 variables related to the geometric characteristics of the manoeuvring area were collected, including: the number of runways (RWY), taxiway (TWY) segments, and conflict points (RWY / RWY, RWY / TWY, TWY / TWY). When analysing aeronautical charts from the different countries, inconsistencies were identified (i.e. how taxiways are labelled and counted). Therefore, this thesis considers the number of taxiway segments rather than the number of taxiways. A taxiway segment is defined as a piece of taxiway between two conflict points A and B.

A conflict point is a point on the airport surface where two parties (i.e. aircraft, V/PD) could conflict with each other, e.g. a crossing. Seven types of conflict points are

considered, i.e. Type 2 conflict point – Type 8 conflict point. The number of the type corresponds to the number of taxiway segments in conflict with each other. For example, in a case where two taxiways cross each other (Figure 122), four taxiway segments are in conflict with each other, since each of the four taxiway segments could be occupied by an aircraft or V/PD. Each conflict point can occur in three variations: conflict point RWY / RWY, conflict point RWY / TWY, and conflict point TWY / TWY. Figure 120 to Figure 126 show examples of Type 2 to Type 8 conflict points for taxiways. Figure 127 illustrates an example of a Type 6 conflict point RWY / TWY.

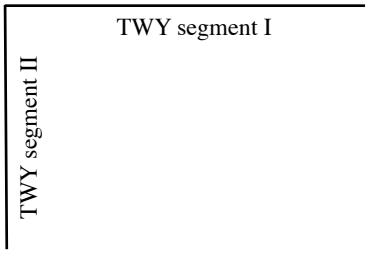


Figure 120: Type 2 conflict point (TWY / TWY)

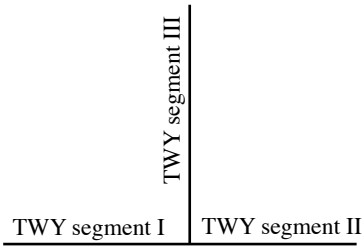


Figure 121: Type 3 conflict point (TWY / TWY)

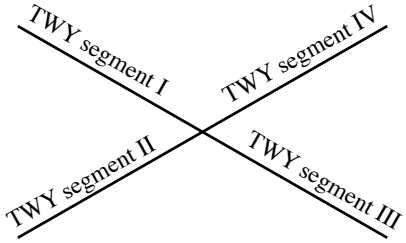


Figure 122: Type 4 conflict point (TWY / TWY)

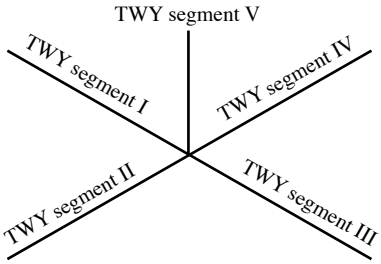


Figure 123: Type 5 conflict point (TWY / TWY)

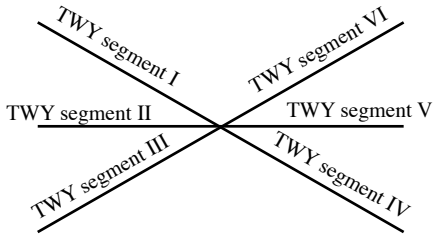


Figure 124: Type 6 conflict points (TWY / TWY)

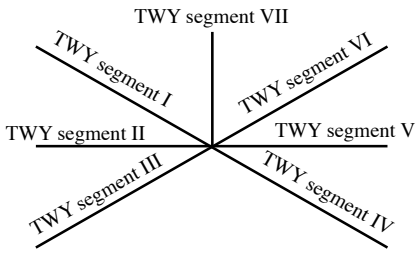


Figure 125: Type 7 conflict points (TWY / TWY)

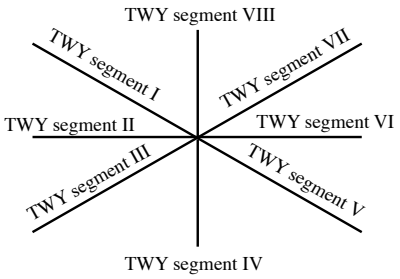


Figure 126: Type 8 conflict points (TWY / TWY)

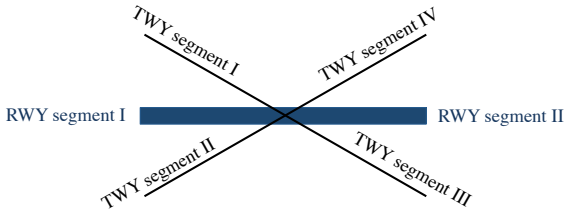


Figure 127: Type 6 conflict point (RWY / TWY)

The characteristics of the physical layout of the manoeuvring area are described in Table 65. The number of runways at the sampled airports ranges from single runways up to seven. The number of taxiway segments ranges widely from only two to 327 at the most complex airport. The most frequent type of conflict point is Type 3 conflict points, with a mean of 27.67 Type 3 conflict points at an airport. The sample contains only low numbers of RWY / RWY conflict points, i.e. two runways crossing each other without a taxiway crossing in the same location. The maximum number of RWY / RWY conflicts identified was seven. The number of TWY / TWY conflict points on the other hand reached 128 at its maximum. The maximum total number of conflict points (i.e. RWY / RWY + RWY / TWY + TWY / TWY) ranged from two to 207, indicating the number of points at an airport where at least two parties may come into conflict with each other. Multiplying this number by the number of taxiway segments involved in these conflicts, the total number of segments in conflict with each other reaches a maximum of 777 taxiway segments with a mean of 156.54.

Table 65: Descriptives - manoeuvring area characteristics

Variable	Data type	N	Min	Max	Range	Mean	SD	Nor-mality
Number of runways	Continuous	52	1	7	6	2.29	1.65	✗
Number of taxiway segments	Continuous	52	2	327	325	67.54	79.06	✗
Number of Type 2 conflict points	Continuous	52	0	17	17	6.08	4.40	✗
Number of Type 3 conflict points	Continuous	52	0	114	114	27.67	30.37	✗
Number of Type 4 conflict points	Continuous	52	0	84	84	13.08	17.88	✗
Number of Type 5 conflict points	Continuous	52	0	19	19	1.44	2.99	✗
Number of Type 6 conflict points	Continuous	52	0	8	8	0.31	1.20	✗
Number of Type 7 conflict points	Continuous	52	0	3	3	.10	.50	✗
Number of Type 8 conflict points	Continuous	52	0	1	1	.02	.139	✗
Total number of conflict points RWY/RWY	Continuous	52	0	7	7	.50	1.23	✗
Total number of conflict points RWY/TWY	Continuous	52	1	79	78	14.85	16.18	✗
Total number of conflict points TWY/TWY	Continuous	52	0	128	128	31.60	36.25	✗
Total number of conflict points at the airport	Continuous	52	2	207	205	46.94	51.83	✗
Total number of segments in conflict with each other	Continuous	52	6	777	771	156.54	178.53	✗

10.3.1.5 Equipment and Installations

The mean number of communication channels is 5.84 per airport and the number of frequencies can reach a maximum of 31, see Table 66. In addition, the airport operators were asked whether they had experienced any situations in which their equipment did not adequately support their operations. For example, an airport may have an ILS CAT I runway, but may need a higher category for safe and efficient operations. A total of 13.5% of airports were dissatisfied with their equipment and installations.

Table 66: Descriptives - equipment and installations

Variable	Data type	N	Min	Max	Range	Mean	SD	Normality
Number of communication channels	Continuous	51	1	11	10	5.84	3.19	✗
Number of frequencies	Continuous	51	1	31	30	12.18	8.78	✗
Adequacy of equipment / installations	Nominal categorical	52	• Adequate: 86.5% • Not adequate: 13.5%					

10.3.1.6 Visual Navigation Aids

When asked to evaluate the adequacy of their visual navigation aids, 92.3% of airport operators indicated adequacy. In addition, when questioned regarding complaints about lighting, markings and signage at their airports airport operators reported the following: 13.4% had problems with lighting, 23.0% with markings, and 25.0% with signage. The results are summarised in Table 67.

Table 67: Descriptives - visual navigation aids

Variable	Data type	N	Response categories: frequency distribution
Adequacy of visual navigation aids	Nominal categorical	52	• Adequate: 92.3% • Not adequate: 7.7%
Complaints about lighting	Ordinal categorical	52	• Yes, 10-30: 1.9% • Yes, <10: 11.5% • No: 86.5%
Complaints about markings	Ordinal categorical	52	• Yes, 10-30: 3.8% • Yes, <10: 19.2% • No: 76.9%
Complaints about signage	Ordinal categorical	52	• Yes, 10-30: 5.8% • Yes, <10: 19.2% • No: 75.0%

10.3.1.7 Airfield Operations and Maintenance

The majority of airports (88.5%) used subcontractors for construction or maintenance work on the manoeuvring area. Typically, maintenance work was necessary weekly at 73.1% of airports. Among vehicle drivers operating on the surface, certain vehicles were allowed to operate ‘free-range’ in 23.1% of the airports, i.e. vehicles did not need to

contact ATC when moving on the surface, with the exception of active runways. In 17.3% of the airports not all the vehicles are equipped with radio communication. The number of runway condition checks conducted per day ranged from 1 to 14 with a mean value of 5.33 checks per day. Finally, 55.8% of airports use runways as taxiways, however for 17.3% this is not a standard operating procedure. Table 68 shows the details.

Table 68: Descriptives - operations and maintenance

Variable	Data type	N	Min	Max	Range	Mean	SD	Normality
Subcontractors working on the airfield	Nominal categorical	52	• Yes: 88.5% • No: 11.5%					
Number of runway condition checks / day	Continuous	52	1	14	13	5.33	3.65	✗
Use of runways as taxiways	Nominal categorical	52	• Yes, standard procedure: 38.5% • Yes, non-standard procedure: 17.3% • No: 44.2%					
Requirement for clearance for vehicle drivers	Nominal categorical	52	• All of them: 76.9% • Some of them: 23.1%					
Vehicle equipment with radio communication	Nominal categorical	52	• Yes, all of them: 80.8% • Yes, some of them: 17.3% • No: 1.9%					
Frequency of maintenance work	Ordinal categorical	51	• Weekly: 73.1% • Monthly: 7.7% • Every 2-3 month: 3.8% • Every 4-6 month: 9.6% • More than 6 month: 3.8% • Missing: 1.9%					

10.3.1.8 Regulations

Of the sampled airports, 82.7% engage in proactive safety assessments apart from regulatory requirements (Table 69).

Table 69: Descriptives - regulations

Variable	Data type	N	Response categories: frequency distribution
Engagement in proactive safety assessments	Nominal categorical	52	• Yes: 82.7% • No: 17.3%

10.3.1.9 Human Resources

The last section of the questionnaire required the airport operators to evaluate the adequacy of their level of staffing and training. The results are summarised in Table 70. A total of 82.7% evaluated their staffing level as adequate and only one airport evaluated the level of training of its staff as inadequate. In addition, 11.5% of airport operators indicated that the training of subcontractors was inadequate.

Table 70: Descriptives - human resources

Variable	Data type	N	Response categories: frequency distribution
Adequacy of staffing level	Nominal categorical	52	• Adequate: 82.7% • Under-staffed: 17.3%
Adequacy of training for operational personal	Nominal categorical	52	• Yes: 98.1% • No: 1.9%
Adequacy of training for subcontractors	Nominal categorical	49	• Yes: 82.7% • No: 11.5% • Missing: 5.8%

10.3.1.10 Outliers

Following the high-level analysis the data was analysed for outliers (i.e. data points that are not consistent with the others within a sample from the same population). The data was tested for outliers both, at the aggregated level and at the State-level.

While outliers exist, it is highly questionable as to whether to exclude these. For example, in the UK, London Heathrow was shown as an outlier among several variables (e.g. average annual movements, number of taxiway segments). Likewise, Oslo Lufthavn was shown as an outlier for Norway. These airports are characteristic for their countries. Both Heathrow and Oslo are the biggest airports in respective countries in terms of movements and passenger boardings. Both airports accommodate international flights and serve as main country hubs. If removed, the typical characteristics of the underlying national airport infrastructures would consequently be removed. Therefore, it was decided to create two datasets, one including outliers and one excluding outliers, and the statistical tests were run on both datasets in order to assess the influence of outliers on the results.

10.3.2 Data Distribution

The continuous variables were tested for normality and as sections 10.3.1.2 to 10.3.1.9 showed the majority of variables were found to be non-normal. The test statistics are shown in Appendix VIII Table 1. The implication of this is that non-parametric statistical tests needed to be applied for most of the variables. Similarly, categorical data required the application of non-parametric tests. In addition to testing the aggregated data for normality, the data was also tested at the national level with similar results, the majority of variables were found to be non-normal. Appendix VIII Table 4 summarises the test statistics.

10.3.3 Data Homogeneity

Before a detailed analysis, the data was tested for homogeneity and the consequent potential for aggregation. The non-parametric Kruskal-Wallis and Pearson Chi-Square tests were applied to test whether samples originate from the same population. The homogeneity of the four countries in terms of airport characteristics, normalised number of occurrences, and causal factors was tested and the results show significant differences across the countries at the 95% confidence level (Kruskal Wallis $p < .05$; Pearson Chi-Square $p < .05$). Therefore, safety occurrence data and airport data from different countries should not be aggregated. In addition, attempts to aggregate the European data (i.e. UK and NO) showed also significant differences between the countries (Mann Whitney $p < .05$; Pearson Chi-Square $p < .05$). The test statistics of the homogeneity tests are given in Appendix VIII Table 2.

To illustrate this finding further, the normalised number of incursions (per 100,000 movements) aggregated across the four countries (sample of 52 airports) was correlated with the collected airport characteristics data and the majority of tested variables showed significant correlations as shown in Appendix VIII Table 3.

When referring back to the underlying data, however, it becomes clear that these correlations are less meaningful. For example, the rate of incursions (per 100,000 movements) is negatively correlated to the number of runways and taxiway segments. This indicates that the higher the number of runways and taxiway segments the fewer incursions occur. Figures 128 and 129 highlight that this interpretation should not be generalised.

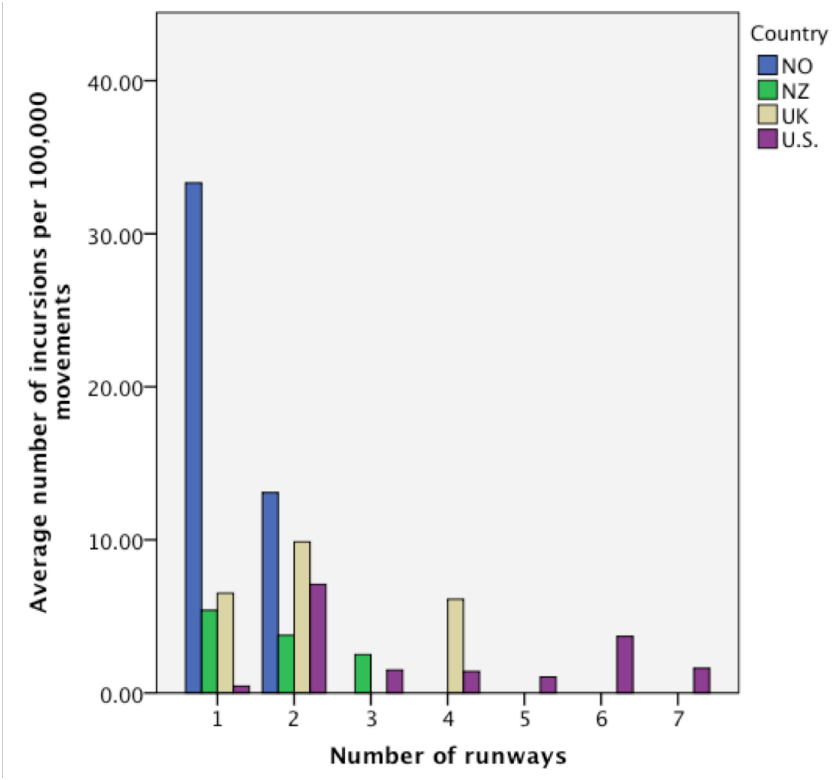


Figure 128: Normalised number of incursions (aggregated) vs. number of runways

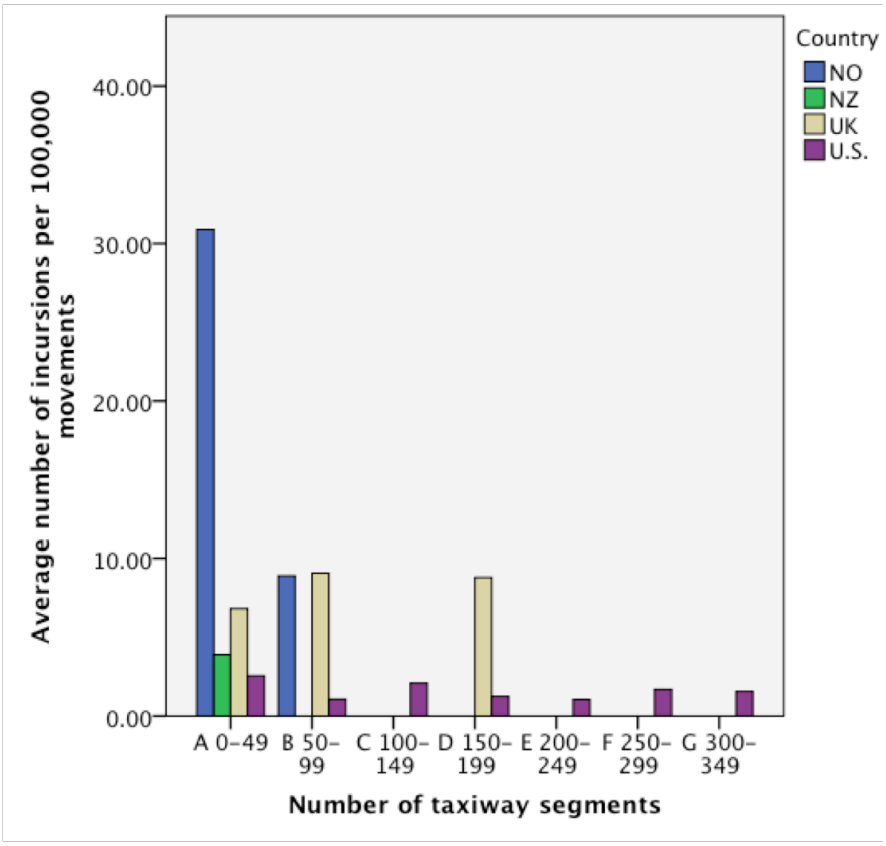


Figure 129: Normalised number of incursions (aggregated) vs. number of taxiway segments

Figures 128 and 129 illustrate that if an airport shows the typical characteristics of a Norwegian airport (blue) then it will show a high number of incursions, whereas if an airport looks like a typical airport in the U.S. (purple) then incursions occur very rarely. These two examples illustrate that the statistical analysis is heavily biased by the reported occurrence rate in the four countries and differences in the underlying airport infrastructures. The different occurrence rates are a result of different reporting levels in the considered countries. Therefore, it would not be sensible to aggregate such data across countries. This confirms the results from the homogeneity tests and corresponds to the conclusions drawn from the data quality assessment in Chapter 6.

This analysis was computed using the whole data set. Due to the differences among the four countries, outliers cannot be removed, as this would lead to the removal of a significant amount of data from specific countries. For example, the normalised number of incursions was shown as being an outlier for most Norwegian airports. Similarly, the majority of U.S. airports were shown as outliers with respect to their average annual movements for example.

10.3.4 Analysis for Associations

The data was tested for associations between airport characteristics and i) the rate of accidents / incidents per occurrence type, ii) the severity of accidents / incidents per occurrence type, and iii) the causal factors that underlie occurrences.

Since the data cannot be aggregated across countries, each country was analysed separately. In NZ, only three airports responded to the questionnaire survey, and therefore, statistical analysis was not possible. Also, the airport characteristics may influence the three considered accident / incident types differently, and hence, each occurrence type was analysed separately. The data quality assessment in Chapter 6 concluded that excursion and FOD data in the U.S. are underreported due to a lack of a regulatory requirement to report such incidents, and consequently, this data was excluded from the assessment (i.e. U.S data refers to incursions only).

An analysis for associations between airport characteristics and severity levels in the U.S. was only possible for runway incursions reported after 1 October 2007. The frequency analysis showed that high-severity categories A and B occurred only four times during the considered time period. This amount was too small to be used for statistical

analysis, and therefore, the data was analysed for associations between airport characteristics and severity categories C and D. Similarly, in the UK only 0.9% of occurrences were classified as severe and highly severe (Cat A and B), and for this reason only categories C and D were taken into account. The categorisation of occurrences into accidents, serious incidents and incidents in Norway did not allow for statistical analysis since 99.7% of occurrences were classified as incidents.

Finally, the data was analysed for associations between airport characteristics and the causal factors extracted from accident / incident reports. The causal factors are summarised at the highest taxonomy level into the three groups of aircraft operations, ATC and airport operations. Environmental factors, which mainly related to weather, were excluded, since airport characteristics do not influence the occurrence of weather. Regulatory factors were also excluded from the analysis due to their low frequency. Whilst the association between airport characteristics and occurrence rates was analysed for each of the accident / incident types separately, this analysis is not split by occurrence type. The aim was to identify whether airport characteristics influence the occurrence of causal factors at airports in general. Knowing which types of causal factors to expect at an airport can then be used to channel risk mitigation efforts regardless of the occurrence type.

10.3.4.1 Results

Table 71 contains the results and significant associations (at the 95% - level) are highlighted by means of a tick (✔). The analyses were conducted for both a complete set of data and a data file excluding outliers. Since the results varied only marginally, Table 71 presents the results for the whole data set. The results for the dataset excluding outliers are shown in Appendix VIII Table 5. The test statistics for both, analyses including and excluding outliers, are shown in Appendix VIII Tables 6 to 18.

Table 71: Summary of significant associations

Airport characteristic	Rate of occurrences							Severity		Causal factors		
	Incursions			Excursions		FOD						
	U.S.	UK	NO	UK	NO	UK	NO	U.S. *	UK **	U.S.	UK	NO
Average annual movements	-	-	✔	-	-	-	-	✔	-	✔	✔	✔
Altitude	-	-	-	✔	-	-	-	-	-	✔	✔	✔
Peak number of operations	-	-	-	-	-	-	-	✔	-	✔	✔	✔
Number of runways	-	-	-	-	-	-	-	✔	-	✔	✔	✔
Number of taxiway segments	-	-	-	-	-	-	-	✔	-	✔	-	✔
Number of Type 2 conflict points	✔	-	-	-	-	-	-	-	-	✔	✔	✔
Number of Type 3 conflict points	-	-	-	-	-	-	-	✔	-	✔	✔	✔
Number of Type 4 conflict points	-	-	-	-	-	-	-	✔	-	✔	-	-
Number of Type 5 conflict points	-	-	-	-	-	-	-	✔	-	✔	-	-
Number of Type 6 conflict points	-	-	-	-	-	-	-	✔	-	✔	✔	-
Total number of conflict points RWY-RWY	✔	-	-	-	-	-	-	-	-	-	✔	-
Total number of conflict points RWY-TWY	-	-	-	-	-	-	-	✔	-	✔	✔	✔
Total number of conflict points TWY-TWY	-	-	-	-	-	-	-	✔	-	✔	-	✔
Total number of conflict points at the airport	-	-	-	-	-	-	-	✔	-	✔	-	✔
Total number of segments in conflict with each other	-	-	-	-	-	-	-	✔	-	✔	-	✔
Number of communication channels	-	-	-	-	-	-	-	✔	-	✔	✔	✔
Number of frequencies	-	-	-	-	-	-	-	✔	-	-	-	✔
Adequacy of equipment		-	-	-	-	-	-	-[a]	-[a]	-[a]	✔	-[a]
Adequacy of visual aids	-	-	-	-	-	-	-	-[a]	n/a	-[a]	n/a	-[a]
Complaints about lighting	-	-	-	-	✔	-	-	✔	-	✔	-	✔[a]
Complaints about marking	-	-	-	-	-	-	-	-[a]	-	✔[a]	-	✔
Complaints about signage	-	-	-	-	-	-	-	-[a]	-	✔[a]	-	✔
Frequency of maintenance / construction work	-	-	-	-	-	-	-	n/a	n/a	n/a	n/a	✔[a]
Subcontractors working on the airfield	✔	-	-	-	-	-	✔	-	-[a]	✔	✔[a]	-
Requirement of clearances for all vehicle drivers	-	-	-	-	-	-	-	-	-	✔	✔	n/a
Vehicle equipment with radio communication	-	-	-	-	-	-	-	-	-	✔	✔	n/a
Number of runway condition checks	-	✔	-	-	-	-	-	✔	-	✔	-	✔
Use of runways as taxiways	-	-	-	-	-	-	-	✔	-	✔	✔[a]	✔
Engagement in pro-active safety assessments	-	-	-	-	-	-	-	-[a]	-[a]	✔	-[a]	✔
Adequacy of staffing level for airside operations	-	-	-	-	-	-	-	✔	-[a]	✔	-[a]	-
Adequacy of training for operational personnel	-	-	-	-	-	-	-	n/a	n/a	n/a	n/a	n/a
Adequacy of training for sub-contractors	-	-	-	-	-	-	-	-	n/a	✔	n/a	✔

*The associations between airport characteristics and runway incursion severity categories C and D were tested (1 October 2007–2009).
**The associations between airport characteristics and severity categories C and D were tested.
[a]: Tests assumptions are not fulfilled
n/a: The test statistic could not be computed, as one of the variables is a constant.

The results show that most airport characteristics are not associated with the rate of airport surface safety occurrences, which confirms the conclusions from Galle, *et al.* (2010). The lack of associations indicates that the rate of accidents and incidents is not influenced by the prevailing characteristics at a given airport, such as the manoeuvring area geometry.

Although airport characteristics are not associated with occurrence rates, in the U.S., they are associated with the severity of occurrences; in particular, the physical airport

surface design (i.e. geometry). For instance, the number of runways, taxiway segments and conflict points were found to be associated with the severity of runway incursions in the U.S. Other factors e.g. complaints about lighting, or the use of runways as taxiways were also found to be associated to severity. On the contrary, the analysis did not show any associations between airport characteristics and severity in the UK. This could be due to a differing severity classification and a limited range of airport characteristics found in the UK. It may be that airports in the UK are more similar to each other in terms of their underlying characteristics than in the U.S.

Moreover, the results show associations between airport characteristics and those factors that were found to have caused the occurrences through the analysis of safety data. Although there are differences between the countries, the major findings are consistent and the data suggests that:

- A non-standard use of runways as taxiways, and inadequate visual navigation aids (i.e. at airports that experienced complaints about lighting, marking, signage) are associated with pilot-related factors;
- A complex manoeuvring area geometry is associated with pilot and ATC-related factors;
- A lack of radios in vehicles, V/PD free-range operations, the existence of subcontractors on the manoeuvring area, and an inadequate level of training of subcontractors, are each associated with ATC-related factors; and
- Inadequate subcontractor training and the non-engagement of airports in proactive safety assessment are associated with V/PD-related factors.

The observed differences between the analysed countries could be a result of differing distributions of reported occurrence types in the considered countries, and associated differing distributions of causal factors (X^2 = 419.53, p (2-tailed) < .001).

10.3.4.2 Discussion

This chapter introduced a methodology for the assessment of airport hazards that supports the safety risk management of airport surface operations. The methodology, however, is not limited to hazard assessments of surface operations, but is transferrable to all aspects of airports, and aviation in general, e.g. to analyse the impact of airspace characteristics on safety occurrences.

This research is limited in that it only considers risk factors and neglects mitigation measures that might have been implemented. For instance, airports may have a complex geometry with a high potential of conflict. However, if the operators (e.g. airport operator, airline, ATC) are aware of the risk, the necessary procedures and operating scenarios could have been designed to account for that. In this case, the risk factor does exist, but is mitigated so well that it does not affect the operations. Future analysis should take mitigation measures into account. In addition, the analysis is limited by the small sample size (i.e. 14-19 airports per country). A larger sample is required to generalize the findings.

There are two main findings here with the first concerning the quality of reporting systems. The reporting levels were found to be significantly different across the analysed organisations. This confirms the findings from the data quality assessment in Chapter 6. In addition, based on the collected variables, the airport infrastructure and operations were found to be significantly different between the countries. Overall, it can be concluded that safety and airport data from different countries cannot be aggregated due to their different underlying distributions. Aggregating such data would lead to unreliable results. This in turn indicates that data-based risk mitigation strategies (e.g. statistical models) can only be valid for individual countries. Although the four analysed countries showed significant differences in their reporting levels, this does not mean that certain countries are 'less safe' than others. It indicates that some countries have a better safety culture and facilitate a more open reporting of occurrences than others. Therefore, there is a scope for sharing best practice.

Secondly, it was found that airport characteristics are not associated with the rate of airport surface safety occurrences. This in turn indicates that airport surface safety occurrences are influenced by other factors, such as human-related factors, and that airport characteristics play a minor role. Nevertheless, it was found that, in the U.S., they are associated with the causal factors that underlie accidents / incidents (e.g. human factors), as well as the severity of occurrences. In these respects, this thesis proves for the first time that associations between airport characteristics and safety occurrences exist. The next chapter will build upon these results to model the functional relationship between airport characteristics, occurrence severity and causal factors, in order to recommend risk mitigation strategies.

10.4 Summary

This chapter introduced a methodology for risk and hazard assessment on the airport surface. Airport characteristics from a sample of 52 airports were collected, and their associations to safety data analysed. It was found that airport characteristics vary significantly across countries and that safety data is not comparable between different states. While there seems to be no association between airport characteristics and the rate of airport surface safety occurrences, the results indicate associations between i) airport characteristics and the severity of occurrences and ii) airport characteristics and the causal factors an airport experiences.

This chapter has provided a novel insight into the impact of airport characteristics on the safety of surface operations, and has laid the foundation for the fulfilment of the seventh research objective. The results are analysed further in the next chapter, which develops a systematic analysis framework to model the functional relationships between airport characteristics, severity and causal factors.

11 Airport Surface Safety Model

The previous chapters have defined airport surface operations and identified the safety drivers. In order to quantify the safety of airport surface operations, this chapter develops a structured framework for the analysis of airport surface safety occurrences and models the functional relationship between accidents / incidents and their underlying causal factors with the aim of fulfilling the seventh research objective.

The chapter starts with the definition of the modelling objective, followed by an introduction of the data used for modelling and a discussion of its distribution. Based on modelling requirements and distribution of the data, an appropriate statistical model is chosen and presented in detail. The second section presents the results of the analysis starting with the specification of a model of the functional relationship between causal factors and occurrences at an aggregated level and discusses why an analysis at this level cannot meet the requirements of SMS. The causal factors are then dissected into six classes and the impact of each category on safety is modelled. To understand the dynamics between the individual categories of causal factors better, the interactions between them are then analysed, before section four summarises the relationships. This is followed by a discussion of the findings and their impact in relation to traditional data collection mechanisms and analysis techniques. Finally, this chapter concludes the analysis presented in this thesis and summarises the findings in a framework for a holistic airport safety management.

11.1 Methodology

11.1.1 Modelling Objective

The architecture of the airport surface system developed during the course of this thesis defined the system components (i.e. human actors and physical infrastructure) and their interactions, and the subsequent analysis of system failures identified the associated causal factors. To determine the most critical causes and to guide safety mitigation efforts more effectively, the functional relationship between the accidents / incidents and the causal factors needs to be modelled using statistical analysis. The lack of robust statistical modelling of causal factors has repeatedly been highlighted during the literature review in Chapter 5. The objective of this chapter, therefore, is to model the functional relationship between airport surface safety occurrences and their underlying causal factors.

Accidents and incidents can be expressed in terms of their safety risk, i.e. in terms of severity and probability. Whilst previous research has attempted to model the probability of occurrences on the airport surface, Chapter 5 highlighted the lack of a robust approach to modelling the severity of accidents / incidents based upon their causes. In addition, it has been shown during the analysis of safety data in Chapters 7 and 8, that all the accident / incident types considered in this thesis occur on a frequent basis and, therefore, it is certain that they will happen again. This chapter, therefore, focuses on modelling their severity in order to gain a better understanding as to why the most severe occurrences happen. The aim is to develop a systematic framework for the analysis of airport surface safety occurrences which can be applied to every dataset in order to identify the most critical causes.

11.1.2 Data Choice and Distribution

The data chosen for this analysis is the U.S. FAA RI Database for the following reasons:

- U.S. airports showed the greatest diversity in terms of airport characteristics (see Appendix X Table 1),
- The severity classification (introduced in Chapter 10 section 10.3.1.1) allows for statistical analysis, and

- Prior analysis (Chapter 10 section 10.3.4.1) revealed associations between airport characteristics, causal factors and severity in the U.S.

The data comprises the characteristics of 19 airports and the corresponding runway incursions that occurred between 1 October 2007 and 31 December 2009. Incursions on taxiways are excluded from the analysis for reasons discussed in Chapter 10 section 10.3.1.1. A total of 283 occurrences were available. Each runway incursion has a severity level assigned and its causal factors were analysed and extracted using the new taxonomy.

11.1.2.1 Runway Incursion Severity Classification

The FAA RI Database assigns a severity category to runway incursions which follows the global standard set by the ICAO and has been introduced in the previous chapter (section 10.3.1.1). The runway incursion severity classification takes several factors into account (Federal Aviation Administration, 2011a):

- Location: Runway incursions concern the incorrect presence of an aircraft on the runway. An unauthorised movement on the airport's movement area excluding the runways is a surface incident;
- Proximity of the aircraft and / or vehicle;
- Geometry of the encounter;
- Evasive or corrective action;
- Available reaction time;
- Environmental conditions, weather, visibility, and surface conditions; and
- Factors that affect system performance.

Detailed guidance for FAA Runway Safety Office staff on the process for: i) determining whether an incident meets the FAA criteria for a runway incursion, and ii) assessing the severity of runway incursions based on FAA and international standards is given in document AJS-RSO-RRI-T03-F-001 (Federal Aviation Administration, 2011a). This involves guidance on the runway incursion data collection process, the runway incursion assessment process, and process measures.

Runway incursions are assessed weekly in a meeting of analysts from the Runway Safety Office who assess the runway incursions systematically using airport layout diagrams, available surface surveillance data and additional information (e.g. human statements, radio communication tapes). If no consensus is reached, the event is

reconsidered and discussed further with other members of staff. The Air Traffic Oversight Service (AOV) may observe the assessment meetings.

The advantage of using the FAA runway severity classification is that it follows a common, global, standardised definition. In addition, the severity assessment process is subject to a strict and audited process. Disadvantages of using this severity classification are the broad definitions of some categories, i.e. in special circumstances the issued severity assessment guidelines may be insufficient. The severity assessment process requires trained analysts. In addition, the runway incursion severity assessment considers only occurrences on the runways. For incursions on taxiways no severity classification is provided, although such occurrences are characterised by similar criteria (e.g. proximity of aircraft and / or vehicle, geometry of encounter, available reaction time). This is yet more evidence of the piecemeal approach to surface safety practiced in the industry and the focus of stakeholders on specific aspects of surface safety.

Overall, the FAA severity classification for runway incursions can be trusted, since i) it follows a global standard, ii) the assessment is done by qualified analysts, iii) the assessment process is audited.

11.1.2.2 Distribution of Severity Categories

The runway incursion severity categories have a logical order from low-severity to high-severity. When modelling such data, the ordinal nature of this data must be accounted for. Table 72 shows the distribution of the severity categories of the 283 analysed runway incursions.

Table 72: Severity distribution U.S. runway incursions Oct 2007 - 2009

Severity classification	Percentage of runway incursions
A	0.4%
B	1.0%
C	50.0%
D	48.6%

High-severity categories A and B are rare, comprising just 1.4% of all occurrences analysed. This amount was too small to be used for statistical analysis, and thus only severity categories C (referred to as high severity in the following unless otherwise stated)

and D (referred to as low severity in the following) were modelled. This reduces the severity classification to a binary variable.

11.1.2.3 Distribution of Causal Factors

The causal factors are categories that do not have a logical order to them and can hence be classified as nominal categorical data. A total of 524 causal factors were extracted from the occurrence reports. Both aircraft and ATC technical factors were each identified only once in the data and were therefore excluded from further analysis. Overall, the considered runway incursions were caused by predominantly human-related factors (70.0% pilot, 14.0% ATC, and 16.0 % V/PD).

11.1.2.4 Distribution of Airport Characteristics

To model the impact of airport physical characteristics on severity the data collected in the previous chapter was used. In particular, variables in relation to the traffic volume (i.e. average annual movements, peak number of operations) and the physical design of the manoeuvring area (i.e. number of runways, taxiway segments, intersections) were analysed. In line with previous research (Simic and Tosic, 2010), traffic and airport surface geometry are used in this chapter as a measure for airport surface complexity since layout and traffic define an airport in its normal state.

The variables are continuous and their distribution is shown in Appendix X Table 1. Since the analysis is based on a small sample of 19 airports the findings should not be generalised for the whole U.S. This chapter rather aims at the development of a methodology for the systematic analysis of airport surface safety occurrences and a practical demonstration of how to apply it using this sub-set of the data.

11.1.3 Model Choice

A statistical tool for estimating relationships between variables is regression analysis. This is a way to predict an outcome variable (i.e. dependent variable (DV)) from one or more predictor variables (i.e. independent variables (IV)) (Field, 2009). This research uses

regression analysis to analyse the relationship between the severity of occurrences and their underlying causal factors in a structured manner.

For categorical outcome variables the logistic regression is applied. There are three types of logistic regression models. If the DV has only two categories, the binary logistic regression is used. When the DV has more than two response categories, the multinomial logistic regression is applied. In cases where the DV is multi-categorical and the categories show an order, the ordinal logistic regression is used (Field, 2009). Logistic regression is commonly used in aviation safety studies (e.g. Biernbaum and Hagemann, 2012; Dupuy, 2012) as well as for other transport modes (e.g. Hu*, et al.*, 2010; Phillips and Sagberg, 2013) where the values or observations of the outcome variable can be sorted according to categories.

Logistic regression is an extension of linear regression that allows the prediction of categorical outcomes based on continuous and / or categorical predictor variables. In particular, it allows the prediction of the probability of the DV occurring, i.e. the probability that a case belongs in a certain category, given known values of the IVs. For a linear regression model to be valid, the observed data needs to contain a linear relationship, where an increase or decrease in one variable (e.g. IV) will cause a corresponding change in another variable (e.g. DV). This assumption is violated when the DV is categorical. Transforming the data using a logarithmic transformation is one way around this problem. Such transformation is a way of expressing a non-linear relationship in a linear way. Thus, the logistic regression equation expresses the linear regression equation in logarithmic terms (called logit) as follows:

$$\mathrm{P(Y)} = \frac{1}{1+e^{-(b_0+b_1X_{1i}+b_2X_{2i}+\cdots+b_nX_{ni})}} \qquad (15)$$

in which *P(Y)* is the probability of *Y* occurring, *e* is the base of the natural logarithms, b_0 is the intercept, and b_n is the regression coefficient of the corresponding predictor variable X_n.

The values of the parameters (i.e. correlation coefficients) are estimated using the maximum likelihood estimation (MLE). MLE is a technique that selects coefficients that maximise the probability of obtaining the observed results; in other words, that make the observed values most likely to have occurred (Agresti, 2007; Field, 2009).

When entering several predictors into a regression model, the method for entry needs to be selected, with both forced entry and stepwise methods available. The forced entry

method whereby all predictors are forced into the model simultaneously has been chosen for the analysis for this thesis for reasons discussed in Appendix IX. Appendix IX also introduces the assumptions underlying logistic regression models and shows how to assess their model fit and how to interpret the results. The odds ratios (Exp(B)) presented in this chapter are computed for 95% confidence intervals.

11.1.4 Modelling Strategy

The safety of the airport surface system can be analysed in four steps as outlined below.

1) High-level analysis

The relationship between the severity of runway incursions and the factors that caused these incidents is first modelled using the aggregate of all causal factors. The Pearson's Chi-Square test for associations and binomial logistic regression analysis are applied.

2) Dissection of the data into its components

While modelling the impact of causal factors on severity at an aggregated level will pinpoint the most crucial factors that need to be addressed, it will lead to only high-level conclusions. To follow SMS principles and, therefore, to be able to give more detailed recommendations, the causal factors must be categorised into groups and each category and their interactions modelled individually. Using the new taxonomy introduced in the previous chapter six categories of causal factors were derived:

- Aircraft / pilot,
- Equipment / ATC,
- Vehicle / V/PD,
- Airport – physical characteristics,
- Environment, and the
- Regulatory system.

The new taxonomy split the causal factors into the five groups of aircraft operations, ATC, airport operations, environment and the regulatory system. In order to capture both, V/PD-

related factors and the impact of the physical airport infrastructure, the category airport operations was split resulting in the six categories shown above.

3) Analysis of the impact of each component on safety individually

To understand the associations in the data better, the data is first plotted and the relationships graphically examined in order to guide further analysis. Subsequently, the data is analysed for associations (Chi-Square test) and the functional relationships between the variables are modelled using logistic regression analysis.

Since the safety data is limited to only human-related factors (i.e. pilot, ATC, V/PD), it is only possible to analyse three of the six proposed categories. Factors related to the physical design of the airport surface and its infrastructure, as well as the environment and the regulatory system were not reported at the 19 airports in the considered time period.

Environmental factors, such as weather, can lead to an incursion when, for instance, fog, haze, or the reflecting sun limits visibility. These factors have been reported in some of the other databases (as identified in Chapter 7) but are missing entirely in the U.S. data and, therefore, cannot be modelled. Inadequate reporting might be the reason for this. Also, regulatory factors were not captured in the data and could therefore not be analysed further.

Referring back to the analysis of causal factors conducted in Chapter 7, other databases also contained reference to the physical characteristics of airports as causes for incursions. To analyse this issue further, the airport characteristics data (i.e. traffic and airport surface geometry) collected in the previous chapter is used to model the relationship between airport characteristics and safety in three steps as outlined below.

i) Modelling the impact of individual airport characteristics on severity:

Binomial logistic regression is applied to estimate the impact of airport characteristics on severity. To begin with, each variable is modelled individually to identify those characteristics that significantly predict the severity of runway incursions.

ii) Development of an overall airport complexity measure:

Building on these results, cluster analysis is applied to group airports in terms of their complexity as defined by traffic volume and manoeuvring area geometry. The aim is to come up with airport complexity categories that could then be related to safety. This would provide a new categorisation of airports in terms of their probability of experiencing high or low severity runway incursions based on airport complexity levels.

Cluster analysis is a technique that groups raw data based on the degree of similarity between cases. A cluster is a group of relatively homogeneous cases. Cases in a cluster are similar to each other and dissimilar to the cases outside the cluster. There are several methods for how the clusters are formed, with most of them working in a hierarchical way. The principle behind each method is similar: beginning with all cases being treated as a cluster in their own right. The clusters are then merged based on a criterion specific to the chosen method. That is, all methods begin with as many clusters as there are cases and end up with just one cluster containing all cases. By inspecting the progression of cluster merging it is possible to isolate clusters of cases with high similarity (Field, 2000).

The airport characteristics that predicted severity best (evaluated by their model fit and prediction rate) as identified in the first step (i) were used as input to cluster airports and the details are discussed in the results section 11.2.2.4. Ward's method, which joins cases into a cluster so that the variance within a cluster is minimised, was chosen as primary method of creating the clusters. In order to see which influence the method has on forming the clusters, alternatives (e.g. between-group linkage, nearest neighbour) were also tried and the results are discussed in section 11.2.2.4.

iii) Modelling the impact of airfield geometry elements on severity:

Finally, airport surface geometry is dissected into its elements and the impact of each of these elements on severity is systematically assessed using binomial logistic regression models. The physical design of the manoeuvring area comprises three elements: the runways, taxiways and intersections (referred to as conflict points in this thesis). Depending on the number of segments in conflict with each other, different types of conflict points can be distinguished (i.e. type 2 to 6). These conflict points again can occur in three variations: RWY / RWY, RWY / TWY, and TWY / TWY. Using binomial logistic regression these elements are modelled in three levels as shown in Figure 130.

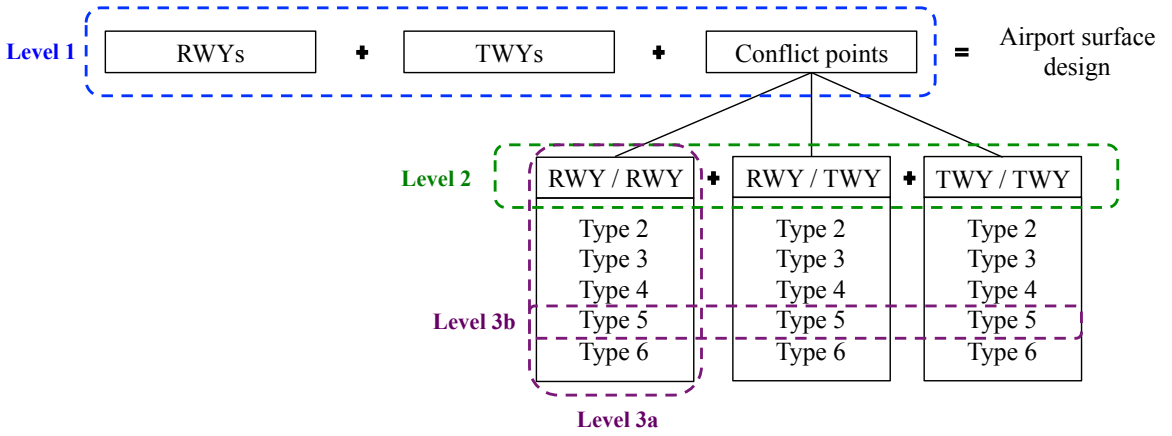


Figure 130: Airport surface design elements

4) Analysis of interactions

After modelling each of the causal factor categories individually, their interactions are analysed. First, human interactions are modelled by assessing the impact on severity of stakeholder interactions (i.e. occurrences that were caused by more than one party) as opposed to occurrences caused by single stakeholders.

To explain how the physical characteristics of the airport surface influences the human-related factors, the functional relationship between airport characteristics and the causal factors extracted from the safety data is subsequently modelled in four steps as outlined below.

i) Modelling the impact of airports on causal factors:

Firstly, the impact of the airport as a whole on the occurrence of causal factors is analysed using contingency tables and the results are discussed in section 11.2.3.2. The aim is to identify whether certain airports attract particular causal factors.

ii) Modelling the impact of airport surface geometry on causal factors (aggregated level):

Subsequently, multinomial logistic regression is employed to analyse whether individual geometric characteristics of the manoeuvring area (e.g. number of runways, taxiway segments, conflict points) influence the causal factors.

iii) Modelling the impact of airport surface geometry on pilots, ATC, V/PD:

Whilst the surface characteristics may not influence the total of causal factors, they might influence particular operations and predict their associated failures. Thus, further analysis splits the causal factors into pilot, ATC and V/PD-related factors and analyses the impact of airport geometric characteristics on these groups of causal factors using multinomial logit models.

iv) Mapping causal factors to airport surface geometry:

Finally, an analysis at the factor-level relates individual runway incursions and their associated causes to the specific locations at the airports where they occurred. To do so, the ten most frequent causal factors extracted from the safety data that could be related to the physical characteristics of an airport were identified for further analysis. For instance, the layout of the manoeuvring area could cause or contribute to the factors 'ATC misjudgement of timings that lead to a situation that was too tight' or 'pilot taxi error', whilst an error in the communication process may not be related to the physical design of the airport surface. The descriptive narratives of the corresponding occurrence reports of 272 causal factors were analysed and by means of airport charts the exact locations of the incidents determined. This detailed analysis assigned each causal factor a corresponding occurrence location and the findings are discussed in section 11.2.3.2.

Figure 131 summarises the analysis framework that quantifies the core of the airport surface system, as shown in Figure 132 in blue.

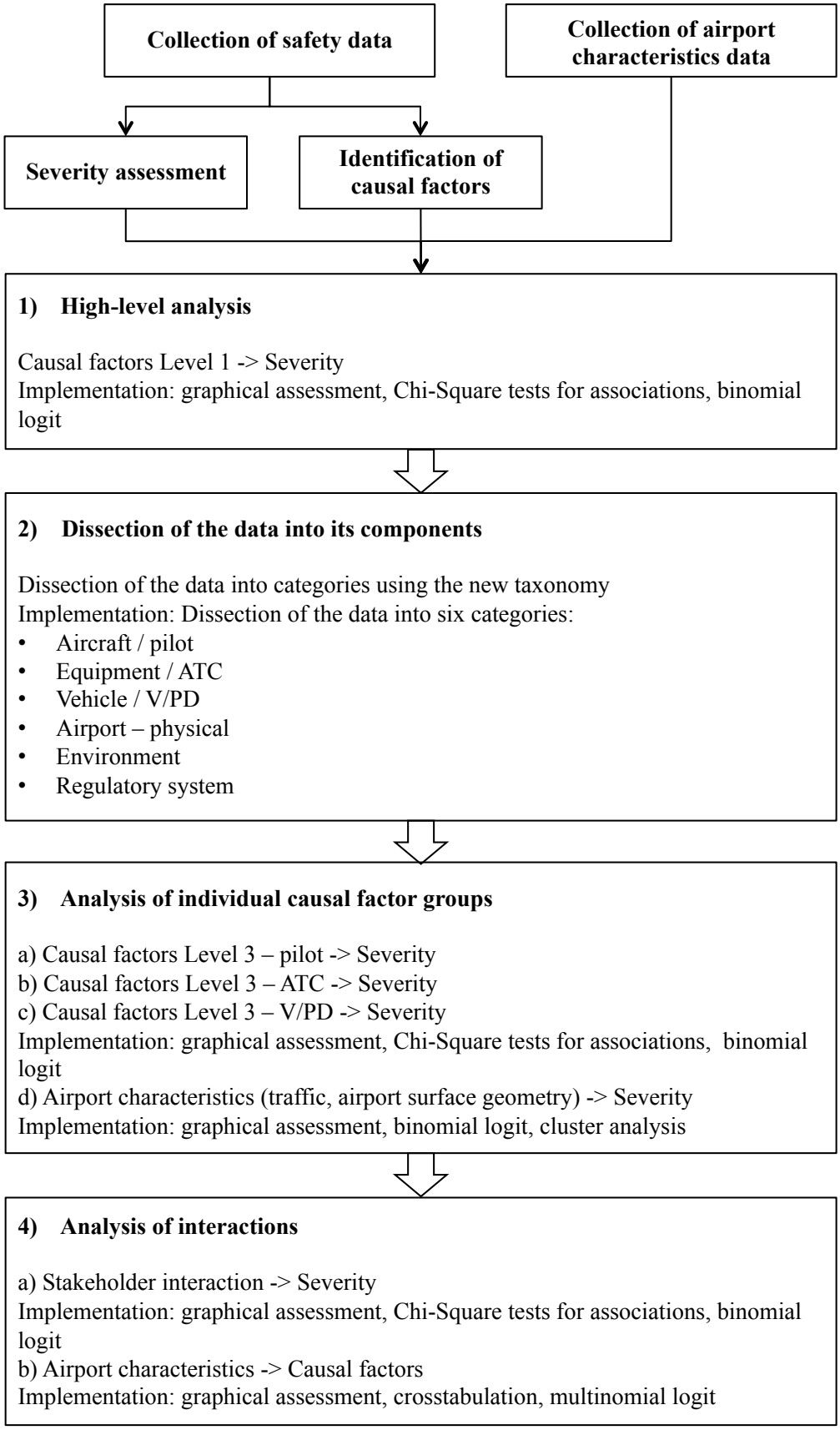


Figure 131: Framework for the systematic analysis of airport surface safety

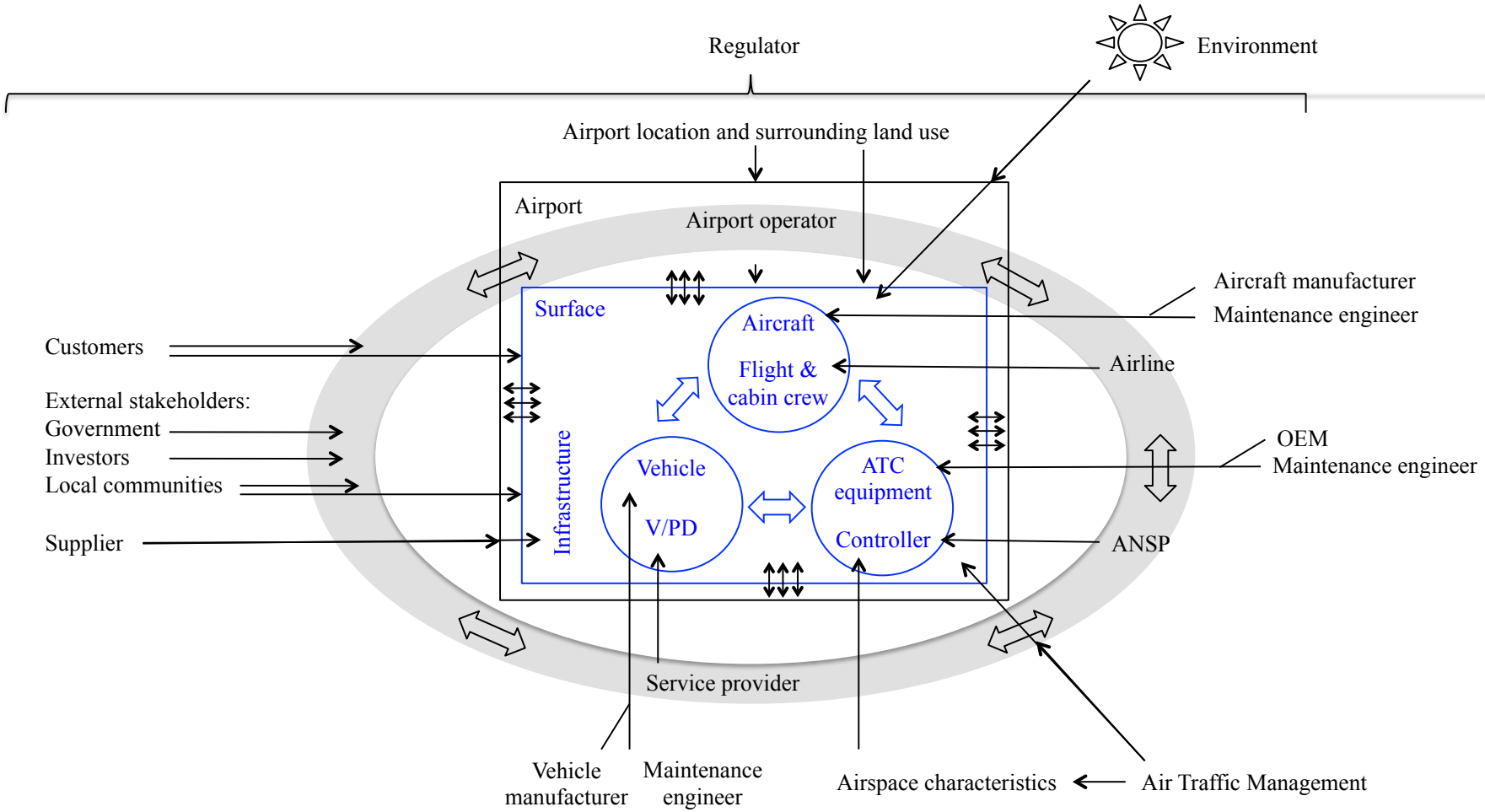


Figure 132: System quantification

11.2 Results

11.2.1 High-level Analysis of Causal Factors

Section 11.1.2 showed the distribution of causal factors across categories at the second taxonomy level. At 70.0%, pilot-related factors contributed most frequently to the analysed runway incursions, followed by V/PD human-related factors (16.0%) and ATC human-related factors (14.0%). Such frequency analyses are often used to guide risk mitigation strategies assuming that the factors occurring most frequently impose the highest risk to the operations. Whilst this is common practice, this approach does not consider the impact of the factors on the outcome (i.e. the severity of an occurrence) and can therefore be misleading, as shown in Figure 133. Figure 133 shows the causal factors (Level 2) across Cat C and D runway incursions and with 90.5% of all ATC human-related factors being associated with high-severity occurrences (i.e. Cat C), ATC's role stands out. Further testing revealed an association between the causal factors (Level 2) and runway incursion severity levels (X^2 (2) = 69.833, p < .001).

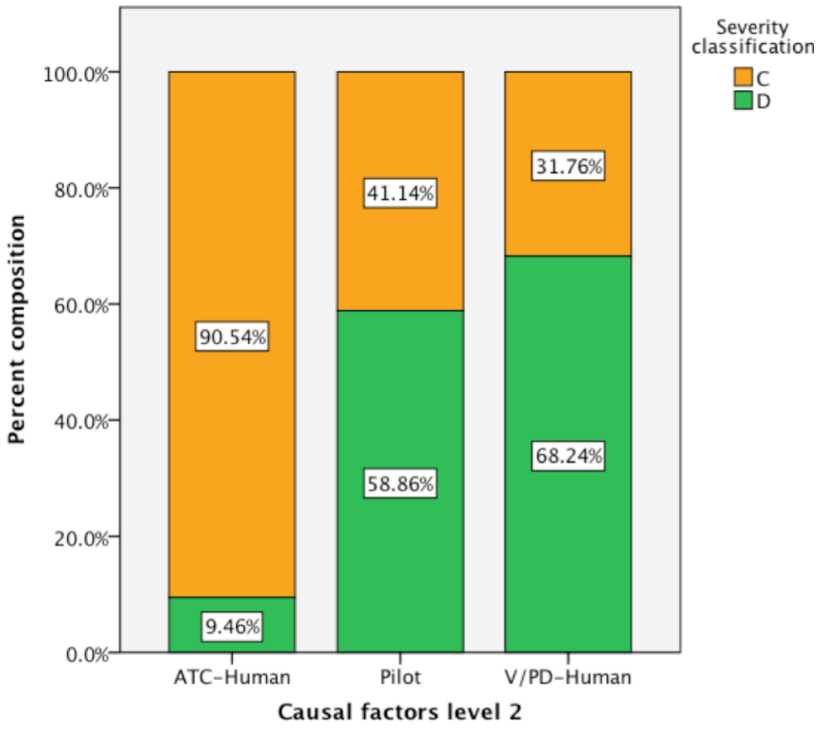


Figure 133: Causal factors (Level 2) across severity categories

To estimate the impact of ATC, binary logistic regression was applied and the contribution of controllers to high-severity occurrences confirmed. ATC (human) was found to be 13.70 times more likely than pilots, and 20.41 times more likely than V/PD (human) to lead to a high-severity occurrence. Table 73 shows the parameter estimates.

Table 73: Parameter estimates causal factors (Level 1) vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity	ATC			45.717	2	.000	
Cat C	Pilot	-2.617	.411	40.510	1	.000	.073
(High)	V/PD	-3.032	.461	43.105	1	.000	.049
	Constant	2.559	.397	32.336	1	.000	9.571

R^2 = .106 (Hosmer&Lemeshow), .136 (Cox&Snell), .182 (Nagelkerke). Model X^2 = 76.934, p < .001.
The DV reference category is Severity Cat D (Low) and the IV reference category is ATC.

Further analysis indicated associations between the causal factors on the third taxonomy level and severity levels (X^2 (16) = 91.189, p < .001), however, with the test assumptions being violated (i.e. 58.8% of cells having an expected count of less than five) the results are invalid. In order to understand the contribution of individual factors better, the following sections break down the causes and analyse pilot, ATC and V/PD human-related factors individually.

11.2.2 Analysis of Individual Groups of Causal Factors

11.2.2.1 Air Traffic Control

The high representation of ATC human-related factors in high-severity Cat C incidents, and, therefore, the skewed distribution towards this category, meant that a more detailed analysis as to which ATC factors are most crucial using logistic regression was not possible and only a frequency analysis could be conducted. Table 74 shows the most frequent ATC human-related factors. For Cat C incidents the top five factors (percentage of total occurrences with ATC contribution) are shown. Only seven ATC human-related factors were extracted from all runway incursions classified as low-severity (Cat D). These are shown in in the third column. Also, the dataset contained four occurrences classified as Cat A and B that were initially excluded from the analysis due to their low frequency of occurrence. ATC was the primary cause for three of them, providing additional evidence

that controllers seem to contribute to high-severity occurrences. The factors extracted from the Cat A/B reports are shown in the first column.

Table 74: Most frequent ATC factors

Category A and B	Category C (%age of total occurrences with ATC contribution)	Category D
ATC misjudgement of timings which lead to a situation that was too tight	ATC misjudgement of timings which lead to a situation that was too tight (17.8%)	Blocked view of the manoeuvring area from ATC tower
ATC did not check whether the aircraft had effectively cleared the runway	ATC - late or inaccurate provision of RWY / TWY condition information (9.6%)	ATC forgetting about the closure of a RWY
ATC issued conflicting clearances	ATC issued conflicting clearances (9.6%)	ATC issued conflicting clearances
ATC - clearance given too early	Inadequate ATC coordination (teamwork) (5.5%)	Inadequate ATC coordination (teamwork)
	ATC did not correct an error in the readback of another party (4.1%)	ATC did not correct an error in the readback of another party
	Others (53.4%)	Communication breakdown between ATC and an aircraft
		ATC thought a readback was correct while it was incorrect

Overall, the factors are a mixture of purely human-related factors (e.g. ATC did not check whether the aircraft had effectively cleared the runway) and human factors that could have been provoked by the design of the airport surface (e.g. issue of conflicting clearances, misjudgement of timings that lead to a situation that was too tight). Consequently, the impact of the airport on surface operations is later analysed in more detail in section 11.2.3.2.

Amongst the four causal factors extracted from Cat A/B occurrences:

- Two were also found amongst the ATC factors identified in Cat C runway incursions (highlighted in orange and blue in Table 74),
- One was found amongst both Cat C and D occurrences (highlighted in yellow), and
- One of the factors was new and not identified amongst Cat C and D occurrences.

This shows that runway incursions with a very high severity (Cat A/B) do not occur for unique reasons and that the causal factors are for the most part the same across severity categories. However, it also shows that the causal factors do not follow the same frequency distribution across severity categories. For instance:

- Two of the factors found in Cat D were neither found in Cat C nor in Cat A/B,

- Two of the factors found in Cat D were also found with a low frequency in Cat C, but not in Cat A/B (highlighted in pink), and
- Three of the factors found in Cat D were amongst the top five Cat C factors (highlighted in green), and one of these was also found in Cat A/B (highlighted in yellow).

This analysis supports the common cause hypothesis tested by Heinrich (1931) which had been introduced in Chapter 4 section 4.2.2 only partially. The theory implies that accidents and incidents share the same causes and that a large number of incidents will lead over time to a smaller number of accidents. Whilst there is evidence that factors found in Cat A and B are also found in low-severity occurrences, their frequency distribution differs and this has implications for safety risk mitigation strategies. Mitigating the causal factors that most frequently lead to Cat C and D occurrences will not mitigate the risk of Cat A and B occurrences.

Due to the overrepresentation of causal factors in Cat C, the analysis of ATC-related factors needs to stop at this level. In summary, this analysis provided evidence that ATC human-related factors have a particular impact on the occurrence of high-severity runway incursions. Referring back to the literature, Biernbaum and Hagemann (2012) drew similar conclusions. The authors analysed runway incursions for the whole U.S. over a ten year period and found that whilst Operational Errors (OE) (i.e. ATC factors) were the least frequent overall, they were overrepresented in severity categories A, B and C, and underrepresented in category D. Logit estimation showed that the odds of a severe incident were 3.4 times as high for events classified as OE as for non-OE events. This study is based on the FAA event classification of runway incursions, which classifies them into OE, pilot deviation (PD) and vehicle / pedestrian deviations (V/PD). This categorisation is not an indication of the cause of the runway incursion; it is a classification of an error type (Federal Aviation Administration, 2013b). These error types typically refer to the last event in the chain of pilot, ATC, and / or V/PD actions that led to the runway incursion and, therefore, Biernbaum and Hagemann's (2012) estimation differs from the one presented in this chapter.

In addition, the current analysis found that the causal factors are, for the most part, the same across severity categories, but differ in terms of their frequencies. This again supports the statement that an analysis of accidents and incidents based on frequencies alone can channel risk mitigation efforts ineffectively. To understand ATC's role better,

further analysis (presented in section 11.2.3.2) will link these factors to the physical characteristics of the airport surface in order to explain under which circumstances ATC deviations occur.

11.2.2.2 Pilot

Concerning pilot-related factors the taxonomy captures eight categories on the third level and five of these were identified in the data. Factors in relation to pilot resources, human-machine interface and team operations were not found in the sample. A graphical assessment of the data shown in Figure 134 indicates that the likelihood of having a high-severity occurrence is highest for incidents that show errors in the communication process, followed by human reliability-related factors. Competence and situational awareness-related factors seem to have a similar impact on severity and procedural factors are mainly associated with low severity. Further testing confirmed an association between pilot human-related factors (level 3) and severity categories (X^2 (4) = 13.898, p < .05).

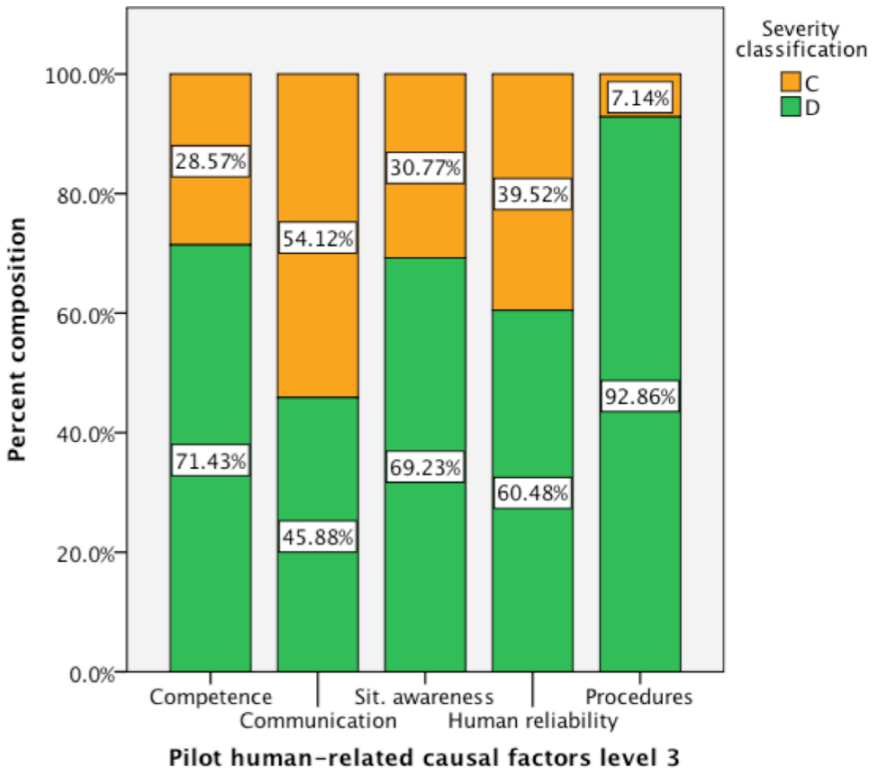


Figure 134: Pilot human-related causal factors (Level 3) across severity categories

Using the binomial logit model the following relationships were revealed:

- The odds of communication-related factors are 1.8 times the odds of human reliability-related factors to result in a high-severity occurrence,
- The odds of communication-related factors are 15.33 times the odds of procedural factors to result in a high severity occurrence,
- The odds of human reliability-related factors are 8.49 the odds of procedures to be classified as high severity, and
- Pilot competence and situational awareness did not contribute significantly to the prediction of severity.

The accuracy of prediction has improved over the baseline model but only by 2.9%, resulting in an overall prediction success of 60.8%. Low R^2 values (Hosmer and Lemeshow, Cox and Snell, Nagelkerke) also indicate a poor model fit. This means that although significant predictors were found they are weak for predicting severity. Table 75 to Table 79 show the estimations.

The communication-related factors extracted most frequently from the data were:

- Incorrect readback (47.6% of all communication-related factors, 10.9% of all pilot human-related factors), and
- Correct readback, followed by an unauthorised manoeuvre (32.1% of all communication-related factors, 7.4% of all pilot human-related factors).

The most frequent human reliability-related factors were:

- Pilot entering a runway without authorisation (32.3% of all human reliability-related factors, 21.8% of all pilot human-related factors),
- Pilot not stopping at the required position (e.g. stop bar) (19.8% of all human reliability-related factors, 13.4% of all pilot human-related factors),
- Pilot crossing the hold line in front of a runway (12.9% of all human reliability-related factors, 8.7% of all pilot human-related factors),
- Pilot entering a taxiway without authorisation / taxi error (12.5% of all human reliability-related factors, 8.5% of all pilot human-related factors), and
- Pilot non-compliance with ATC instructions (12.1% of all human reliability-related factors, 8.2% of all pilot human-related factors).

To understand the reasons behind the weak predictions, the frequencies of pilot-related factors were analysed at the third level of the taxonomy. 67.6% of all pilot-related factors are attributed to human reliability and comprise mainly the top five factors that have been shown above (these together account for 60.5% of all pilot-related factors). None of these

factors reflects a cause of an incident. Rather, they represent high-level 'outcomes' providing evidence that the causal factors of pilot-related occurrences are to a large extent not properly attributed and, therefore, cannot be modelled.

Table 75: Parameter estimates pilot human-related factors (Level 3) vs. severity I

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Communication			11.482	4	.022	
	Situational awareness	-.976	.639	2.332	1	.127	.377
	Human reliability	-.591	.253	5.432	1	.020	.554
	Procedures	-2.730	1.060	6.629	1	.010	.065
	Competence	-1.081	.865	1.565	1	.211	.339
	Constant	.165	.218	.575	1	.448	1.179

R^2 = .031 (Hosmer&Lemeshow), .041 (Cox&Snell), .056 (Nagelkerke). Model X^2 = 15.493, p < .05.
The DV reference category is Severity Cat D (Low) and the IV reference category is communication.

Table 76: Parameter estimates pilot human-related factors (Level 3) vs. severity II

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Human reliability			11.482	4	.022	
	Procedures	-2.139	1.046	4.184	1	.041	.118
	Competence	-.491	.847	.336	1	.562	.612
	Communication	.591	.253	5.432	1	.020	1.805
	Situational awareness	-.385	.615	.393	1	.531	.680
	Constant	-.426	.130	10.740	1	.001	.653

R^2 = .031 (Hosmer&Lemeshow), .041 (Cox&Snell), .056 (Nagelkerke). Model X^2 = 15.493, p < .05.
The DV reference category is Severity Cat D (Low) and the IV reference category is human reliability.

Table 77: Parameter estimates pilot human-related factors (Level 3) vs. severity III

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Procedures			11.482	4	.022	
	Competence	1.649	1.333	1.530	1	.216	5.200
	Communication	2.730	1.060	6.629	1	.010	15.333
	Situational awareness	1.754	1.199	2.139	1	.144	5.778
	Human reliability	2.139	1.046	4.184	1	.041	8.493
	Constant	-2.565	1.038	6.109	1	.013	.077

R^2 = .031 (Hosmer&Lemeshow), .041 (Cox&Snell), .056 (Nagelkerke). Model X^2 = 15.493, p < .05.
The DV reference category is Severity Cat D (Low) and the IV reference category is procedures.

Table 78: Parameter estimates pilot human-related factors (Level 3) vs. severity IV

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Competence			11.482	4	.022	
	Communication	1.081	.865	1.565	1	.211	2.949
	Situational awareness	.105	1.030	.010	1	.919	1.111
	Human reliability	.491	.847	.336	1	.562	1.633
	Procedures	-1.649	1.333	1.530	1	.216	.192
	Constant	-.916	.837	1.199	1	.273	.400

R^2 = .031 (Hosmer&Lemeshow), .041 (Cox&Snell), .056 (Nagelkerke). Model X^2 = 15.493, p < .05.
The DV reference category is Severity Cat D (Low) and the IV reference category is competence.

Table 79: Parameter estimates pilot human-related factors (Level 3) vs. severity V

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Situational awareness			11.482	4	.022	
	Human reliability	.385	.615	.393	1	.531	1.470
	Procedures	-1.754	1.199	2.139	1	.144	.173
	Competence	-.105	1.030	.010	1	.919	.900
	Communication	.976	.639	2.332	1	.127	2.654
	Constant	-.811	.601	1.821	1	.177	.444

R^2 = .031 (Hosmer&Lemeshow), .041 (Cox&Snell), .056 (Nagelkerke). Model X^2 = 15.493, p < .05.
The DV reference category is Severity Cat D (Low) and the IV reference category is situational awareness.

11.2.2.3 Vehicle Driver / Pedestrian

A total of 84 causal factors that relate to V/PD-human were extracted from the safety data. With 89.3% of these factors falling into the category of V/PD human reliability-related factors the distribution of factors at the third taxonomy level is heavily skewed and logistic regression was not significant at this level.

Amongst the V/PD human reliability-related causal factors, three factors dominated, representing 72.2% of all such factors:

- V/PD entering a runway without clearance (48.0% of all human reliability-related factors, 41.7% of all V/PD human-related factors),
- V/PD not stopping at the required position (e.g. stop bar) (23.3% of all human reliability-related factors, 20.0% of all V/PD human-related factors), and
- V/PD entering a taxiway without clearance (12.3% of all human reliability-related factors, 10.6% of all V/PD human-related factors),

As seen during the analysis of pilot-related factors, such factors are generic descriptions that represent more the 'outcome' of an event, rather than its causes. That the causes are not attributed properly is the result of inappropriate reporting and investigation of runway incursions.

Interestingly, an inadequate attribution of causes seems to be only the case for pilot and V/PD-related factors. The ATC-related factors were captured in much more detail and referred to concrete examples of deviations of ATC operations. This could be a reflection of the stakeholder viewpoint represented in the underlying reporting system, which is, in the case of the FAA RI Database, the ANSP perspective. This supports the consistent contention of this thesis that, unless occurrences are captured from the perspectives of all relevant actors, a reporting system will be biased. This is also reflected in the DQI that was developed in Chapter 6. The FAA had the worst DQI's attributed, and future research

should therefore compare the modelling capabilities of other databases in reference to the DQI.

Overall, it has been shown that modelling the causal factors works only on a high-level before the causes become too generic as a result of an inadequate attribution of causes during the reporting process.

11.2.2.4 Airport Characteristics

Getting to the airport level the situation worsens, since none of the occurrence reports captured information about the impact of the airports and their physical characteristics. Thus, the data collected in Chapter 10 was used to analyse the impact of airport characteristics, and in particular traffic and surface geometry, further. The relationship between airport characteristics and severity was assessed graphically and it was found that increasing complexity in some variables seems to be associated with higher severity. For instance, airports with a high number of runways showed a higher percentage of Cat C occurrences. This was the case for the number of runways, the number of type 3 and 4 RWY / TWY conflict points, and the number of type 4 TWY / TWY conflict points, as shown in Figures 135 to 138.

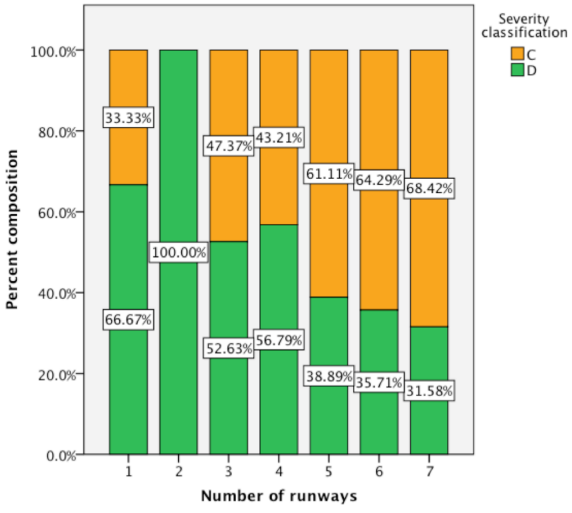


Figure 135: Severity categories across number of runways

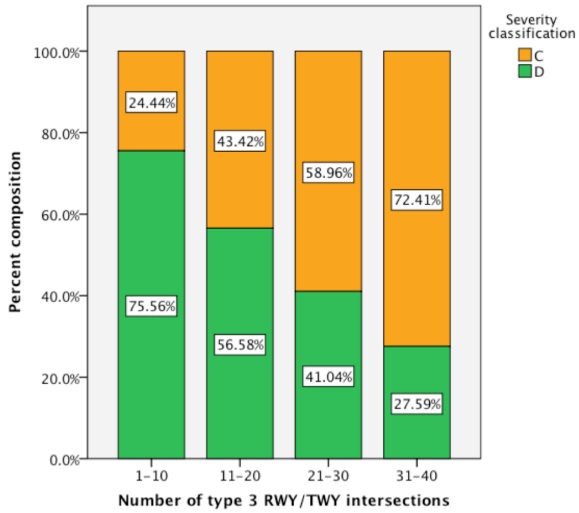


Figure 136: Severity categories across number of type 3 RWY / TWY conflict points

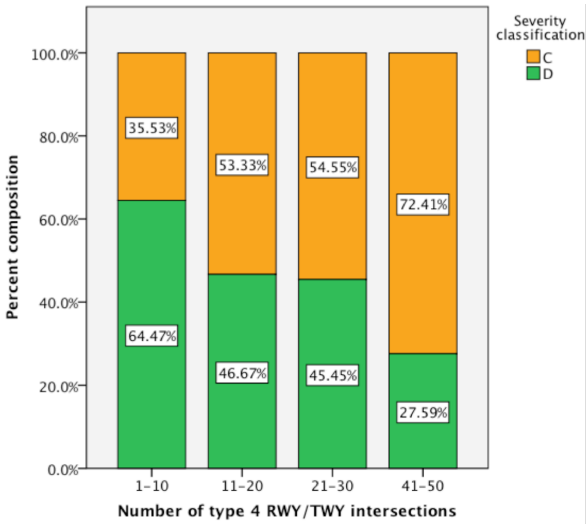


Figure 137: Severity categories across number of type 4 RWY / TWY conflict points

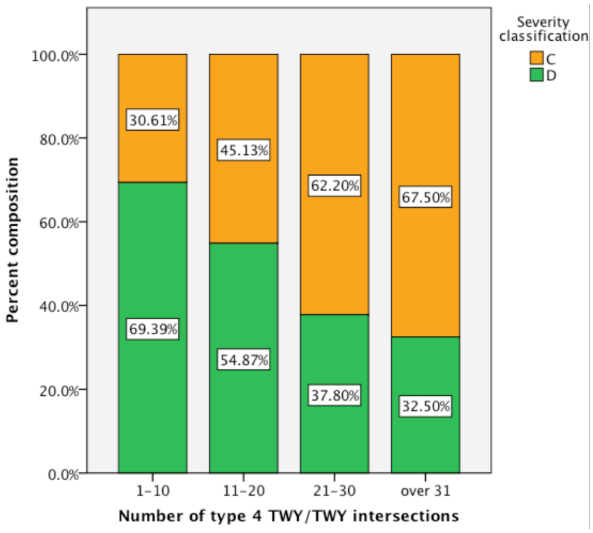


Figure 138: Severity categories across number of type 4 TWY / TWY conflict points

- **Impact of individual airport characteristics on severity**

The previous chapter has already analysed the data for associations and shown that traffic and airport surface design related variables are in particular associated with runway incursion severity levels. To estimate the impact of airport characteristics on severity, binomial logistic regression was applied and to begin with each variable modelled individually. The parameter estimates of all tested variables are shown in Table 80. Some variables could not be modelled due to the absence of certain airport characteristics across the airports (e.g. type 5 RWY / RWY intersection). The parameter estimates given in Table 80 take the complete data set into account for the same reasons as discussed in the previous chapter (i.e. in order to avoid the typical characteristics of the airports are excluded from the analysis). Nonetheless, to analyse the effect of outliers, Appendix X Table 2 contains the parameter estimates based on a data set that excludes all outliers and the findings are discussed below.

The results show that the majority of tested variables are significant predictors for the severity of runway incursions and that, with increasing complexity, the odds of high-severity occurrences increase. Taking the various goodness of fit measures into account, the airport characteristics that predict severity best are the number of runways and taxiway segments and the number of conflict points, in particular type 3 RWY / TWY and type 4 TWY / TWY conflict points. These are highlighted in grey in Table 80. The findings are

the same for the data set excluding outliers, however, the elimination of outliers worsens the model fit.

Table 80: Parameter estimates airport characteristics vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Average annual movements	.000	.000	11.689	1	.001	1.000
	Constant	-.804	.268	9.016	1	.003	.447
	R^2 = .030 (Hosmer&Lemeshow), .042 (Cox&Snell), .056 (Nagelkerke). Model X^2 = 12.193, p < .001.						
Severity Cat C (High)	Peak number of operations	.007	.002	16.789	1	.000	1.007
	Constant	-.756	.220	11.751	1	.001	.470
	R^2 = .047 (Hosmer&Lemeshow), .063 (Cox&Snell), .084 (Nagelkerke). Model X^2 = 18.519, p < .001.						
Severity Cat C (High)*	Number of runways	.419	.084	25.133	1	.000	1.521
	Constant	-1.938	.408	22.546	1	.000	.144
	R^2 = .071 (Hosmer&Lemeshow), .094 (Cox&Snell), .125 (Nagelkerke). Model X^2 = 28.009, p < .001.						
Severity Cat C (High)*	Number of taxiway segments	.005	.001	14.386	1	.000	1.005
	Constant	-.939	.279	11.371	1	.001	.391
	R^2 = .038 (Hosmer&Lemeshow), .052 (Cox&Snell), .069 (Nagelkerke). Model X^2 = 15.142, p < .001.						
Severity Cat C (High)	Number of type 2 RWY/RWY conflict points	-.014	.825	.000	1	.986	.986
	Constant	.014	.120	.014	1	.905	1.014
	R^2 = .000 (Hosmer&Lemeshow), .000 (Cox&Snell), .000 (Nagelkerke). Model X^2 = .000, p > .05.						
Severity Cat C (High)	Number of type 2 RWY/TWY conflict points	-.008	.058	.019	1	.891	.992
	Constant	.033	.182	.033	1	.856	1.034
	R^2 = .000 (Hosmer&Lemeshow), .000 (Cox&Snell), .000 (Nagelkerke). Model X^2 = .019, p > .05.						
Severity Cat C (High)	Number of type 2 TWY/TWY conflict points	.102	.044	5.290	1	.021	1.107
	Constant	-.927	.426	4.736	1	.030	.396
	R^2 = .013 (Hosmer&Lemeshow), .019 (Cox&Snell), .025 (Nagelkerke). Model X^2 = 5.415, p < .05.						
Severity Cat C (High)	Total number of type 2 conflict points	.056	.033	2.826	1	.093	1.057
	Constant	-.635	.404	2.473	1	.116	.530
	R^2 = .000 (Hosmer&Lemeshow), .010 (Cox&Snell), .013 (Nagelkerke). Model X^2 = 2.854, p > .05.						
Severity Cat C (High)	Number of type 3 RWY/RWY conflict points	5.28	.375	1.980	1	.159	1.695
	Constant	-.048	.127	.144	1	.704	.953
	R^2 = .005 (Hosmer&Lemeshow), .007 (Cox&Snell), .009 (Nagelkerke). Model X^2 = 2.030, p > .05.						
Severity Cat C (High)*	Number of type 3 RWY/TWY conflict points	.070	.015	20.499	1	.000	1.072
	Constant	-1.410	.339	17.272	1	.000	.244
	R^2 = .056 (Hosmer&Lemeshow), .076 (Cox&Snell), .101 (Nagelkerke). Model X^2 = 22.393, p < .001.						
Severity Cat C (High)	Number of type 3 TWY/TWY conflict points	.011	.005	5.431	1	.020	1.011
	Constant	-.517	.257	4.036	1	.045	.596
	R^2 = .013 (Hosmer&Lemeshow), .019 (Cox&Snell), .026 (Nagelkerke). Model X^2 = 5.508, p < .05.						
Severity Cat C (High)	Total number of type 3 conflict points	.012	.004	9.505	1	.002	1.012
	Constant	-.794	.289	7.560	1	.006	.452
	R^2 = .024 (Hosmer&Lemeshow), .034 (Cox&Snell), .045 (Nagelkerke). Model X^2 = 9.766, p < .05.						
Severity Cat C (High)	Number of type 4 RWY/RWY conflict points	.110	.069	2.535	1	.111	1.117
	Constant	-.111	.142	.613	1	.434	.895
	R^2 = .006 (Hosmer&Lemeshow), .009 (Cox&Snell), .012 (Nagelkerke). Model X^2 = 2.606, p > .05.						
Severity Cat C (High)	Number of type 4 RWY/TWY conflict points	.041	.013	10.319	1	.001	1.042
	Constant	-.652	.236	7.628	1	.006	.521
	R^2 = .029 (Hosmer&Lemeshow), .039 (Cox&Snell), .053 (Nagelkerke). Model X^2 = 11.422, p < .001.						
Severity Cat C (High)*	Number of type 4 TWY/TWY conflict points	.050	.012	15.955	1	.000	1.051
	Constant	-.937	.266	12.427	1	.000	.392
	R^2 = .044 (Hosmer&Lemeshow), .060 (Cox&Snell), .080 (Nagelkerke). Model X^2 = 17.503, p < .001.						
Severity Cat C (High)	Total number of type 4 conflict points	.027	.007	15.310	1	.000	1.027
	Constant	-.969	.275	12.375	1	.000	.380
	R^2 = .044 (Hosmer&Lemeshow), .060 (Cox&Snell), .079 (Nagelkerke). Model X^2 = 17.427, p < .001.						

Severity Cat C (High)	Number of type 5 RWY/TWY conflict points	.146	.099	2.168	1	.141	1.158
	Constant	-.135	.156	.748	1	.387	.874
	R^2 = .000 (Hosmer&Lemeshow), .008 (Cox&Snell), .010 (Nagelkerke). Model X^2 = 2.195, p > .05.						
Severity Cat C (High)	Number of type 5 TWY/TWY conflict points	.069	.026	7.204	1	.007	1.071
	Constant	-.210	.144	2.151	1	.142	.810
	R^2 = .030 (Hosmer&Lemeshow), .028 (Cox&Snell), .037 (Nagelkerke). Model X^2 = 7.998, p < .05.						
Severity Cat C (High)	Total number of type 5 conflict points	.075	.025	8.658	1	.003	1.078
	Constant	-.306	.158	3.719	1	.054	.737
	R^2 = .024 (Hosmer&Lemeshow), .034 (Cox&Snell), .045 (Nagelkerke). Model X^2 = 9.740, p < .05.						
Severity Cat C (High)	Number of type 6 RWY/TWY conflict points	.479	.233	4.239	1	.040	1.614
	Constant	-.148	.142	1.079	1	.299	.863
	R^2 = .011 (Hosmer&Lemeshow), .015 (Cox&Snell), .020 (Nagelkerke). Model X^2 = 4.348, p < .05.						
Severity Cat C (High)	Number of type 6 TWY/TWY conflict points	.565	.265	4.541	1	.033	1.760
	Constant	-.150	.141	1.117	1	.290	.861
	R^2 = .011 (Hosmer&Lemeshow), .016 (Cox&Snell), .021 (Nagelkerke). Model X^2 = 4.613, p < .05.						
Severity Cat C (High)	Total number of type 6 conflict points	.285	.129	4.857	1	.028	1.330
	Constant	-.165	.144	1.317	1	.251	.848
	R^2 = .012 (Hosmer&Lemeshow), .017 (Cox&Snell), .023 (Nagelkerke). Model X^2 = 4.931, p < .05.						
Severity Cat C (High)	Total number of RWY/RWY conflict points	.096	.060	2.544	1	.111	1.100
	Constant	-.108	.141	.585	1	.444	.898
	R^2 = .006 (Hosmer&Lemeshow), .009 (Cox&Snell), .012 (Nagelkerke). Model X^2 = 2.621, p > .05.						
Severity Cat C (High)	Total number of RWY/TWY conflict points	.029	.007	16.278	1	.000	1.030
	Constant	-1.099	.299	13.511	1	.000	.333
	R^2 = .046 (Hosmer&Lemeshow), .062 (Cox&Snell), .083 (Nagelkerke). Model X^2 = 18.169, p < .001.						
Severity Cat C (High)	Total number of TWY/TWY conflict points	.011	.003	11.470	1	.001	1.012
	Constant	-.904	.297	9.250	1	.002	.405
	R^2 = .030 (Hosmer&Lemeshow), .041 (Cox&Snell), .055 (Nagelkerke). Model X^2 = 11.856, p < .001.						
Severity Cat C (High)	Total number of conflict points at the airport	.009	.002	14.689	1	.000	1.009
	Constant	-1.087	.312	12.134	1	.000	.337
	R^2 = .039 (Hosmer&Lemeshow), .053 (Cox&Snell), .071 (Nagelkerke). Model X^2 = 15.530, p < .001.						
Severity Cat C (High)	Total number of segments in conflict with each other	.003	.001	14.921	1	.000	1.003
	Constant	-1.034	.296	12.183	1	.000	.356
	R^2 = .040 (Hosmer&Lemeshow), .055 (Cox&Snell), .073 (Nagelkerke). Model X^2 = 16.011, p < .001.						

* Variables with the best model fit

- **Airport complexity measure**

Building on these results, cluster analysis was applied to group airports in terms of their complexity as defined by traffic volume and manoeuvring area design. The aim was to come up with airport complexity categories that could then be related to safety. The airport characteristics that predicted severity best as identified in the previous section were used as input to cluster airports. Cluster analysis was performed using various combinations of these variables and available clustering methods. Appendix X Figure 1 and 2 show two examples using:

a) Number of runways, number of taxiway segments, and

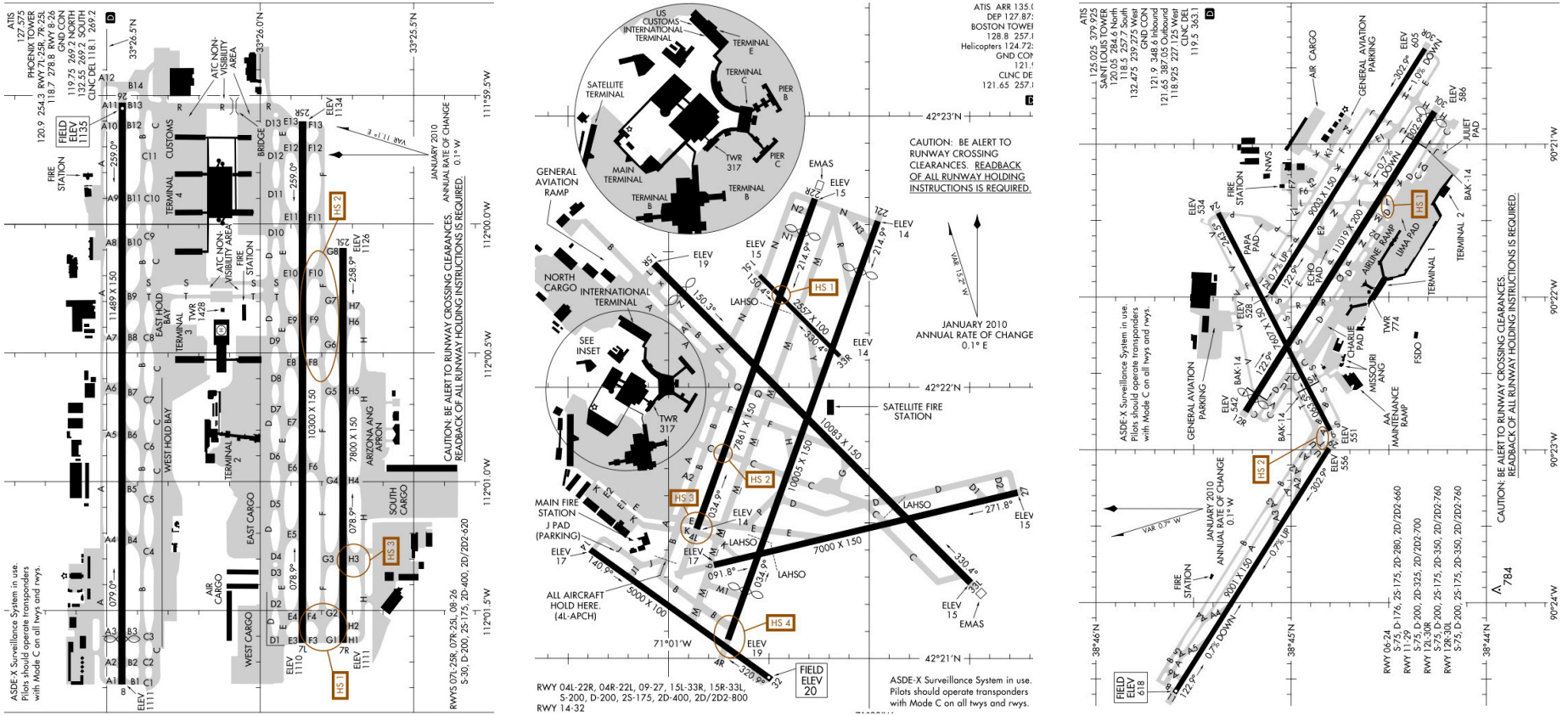
b) Number of runways, number of type 3 RWY / TWY conflict points as inputs.

Ward's method has been used in these examples as method for clustering.

Although the clusters differed depending on the input variables and clustering method, each categorisation showed the same feature: in none of the analyses was it possible to describe the clusters exclusively. For instance, clusters of airports with a small number of runways could show a low, medium or high number of taxiway segments and conflict points, whereas clusters with a high number of runways also showed a mix of a low, medium or high numbers of taxiway segments and conflict points. Categorisations whereby the clusters could be described exclusively worked only when using a single variable as input. For instance, Figure 139 shows an example of three airports that were assigned to the same cluster when categorising them based on their total number of RWY / TWY conflict points.

The airport on the left hand side in Figure 139 has three parallel runways that are surrounded by a network of taxiways. Since the airport has a high number of taxiways which cross the runways it shows predominantly type 4 RWY / TWY conflict points, and at the edge of the runways type 3 RWY / TWY conflict points. The parallel alignment of runways and the crossing taxiways leads to a high number of taxiway segments. In contrast to the first airport, the second has six runways that head in three different directions leading to multiple RYW / RWY intersections. Only two of the runways lie inside the main airport surface and are surrounded by a system of other runways and taxiways. The other four runways lie for the most part on the edge of the airport surface and therefore this airport is dominated by type 2 and 3 RWY / TWY conflict points at locations where the taxiways join the runways. In addition, it shows some type 4 RWY / TWY conflict points and has, overall, fewer taxiway segments than the first airport. The manoeuvring area design of the third airport is a mixture of the other two. It has three parallel runways and one intersecting runway. Two of the parallel runways, as well as the intersecting runway, are surrounded by a taxiway system and show predominantly type 3 and 4 RWY / TWY conflict points. Also, a small number of higher category RWY / TWY conflict points (i.e. type 5 and 6) can be found. The fourth runway lies on the edge of the manoeuvring area and therefore has only type 2 and 3 RWY / TWY conflict points.

This example shows that although the airports are similar in terms of their total number of RWY / TWY conflict points, they are very different in terms of their other characteristics and the particular types of RWY / TWY conflict points.



Source: AirNav.com, 2013

Figure 139: Airport diagrams

Overall, the airports were too different in terms of their characteristics and, therefore, it was not possible to categorise them in terms of complexity. Hence, airport data should not be aggregated. This shows that it is not the complexity of an airport that influences the severity of occurrences; rather, it must be individual characteristics. The following section, therefore, dissects airport characteristics into their elements and analyses which features are the main drivers for severity.

- **Impact of airfield geometry elements on severity**

The physical design of the manoeuvring area comprises the three elements of runways, taxiways and intersections (i.e. conflict points) and binomial logistic regression analysis has been used to model the impact of these elements on severity as introduced in the methodology section (in Figure 130). The results of the analysis are shown in Figure 140 and can be summarised as follow:

- At level 1, the number of runways was a significant predictor for the severity of runway incursions. The odds of having Cat C instead of D runway incursions are 1.666 times higher when the number of runways increases by one unit;
- Testing the airport characteristics at the second level, the total number of RWY / RWY conflict points was found to be a significant predictor for the severity of runway incursions. The change in odds of getting Cat C instead of D is 1.177 when the number of RWY / RWY conflict points increases by one unit;
- At the third level, the elements of the number of RWY / RWY conflict points did not significantly predict severity. That is, airports are not significantly more likely to experience Cat C occurrences when the number of RWY / RWY (type 2, 3 or 4) conflict points increases;
- The number of type 3 RWY / TWY conflict points is a significant predictor for severity and, in particular, a unit increase in type 3 RWY / TWY conflict points increases the odds of getting Cat C instead of D by about 1.115 times;
- The number of type 4 TWY / TWY conflict points was also found to be significant at the third level of analysis, leading to a change in odds of 1.063; and
- When dissecting the number of conflict points further (analysis level 3b), the number of type 4 RWY / RWY conflict points was a significant predictor for the total number of type 4 conflict points, and the odds of having Cat C instead of D

are 1.258 times higher when the number of type 4 RWY / RWY conflict points increases by one unit.

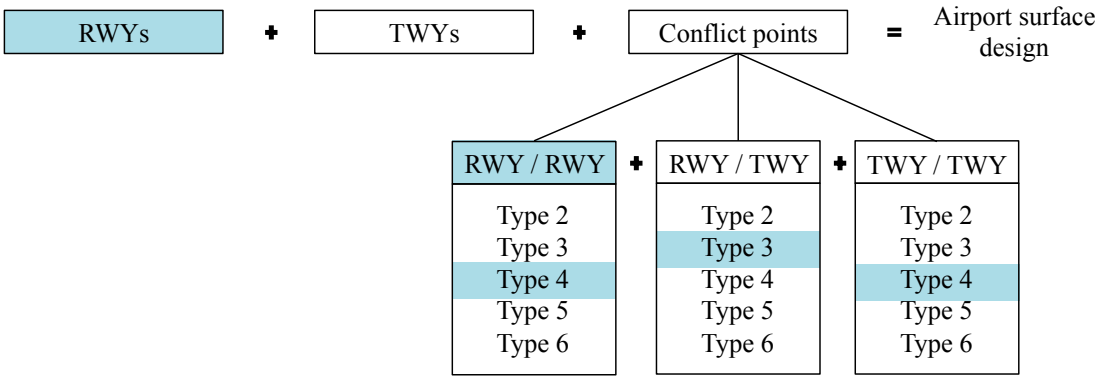


Figure 140: Significant predictors for runway incursion severity

The results are based on the whole data set and Table 81 to Table 86 show the parameter estimates. When excluding outliers, the same significant predictors were identified. Appendix X Tables 3 to 8 contains the calculations.

Table 81: Parameter estimates airport characteristics level 1 vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of runways	.511	.143	12.700	1	.000	1.666
	Number of taxiways	.010	.011	.829	1	.362	1.010
	Total number of conflict points	-.020	.020	.984	1	.321	.980
	Constant	-1.780	.445	15.963	1	.000	.169

R^2 = .074 (Hosmer&Lemeshow), .097 (Cox&Snell), .130 (Nagelkerke). Model X^2 = 29.102, p < .001.

Table 82: Parameter estimates airport characteristics level 2 vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Total number of RWY/RWY conflict points	.163	.072	5.164	1	.023	1.177
	Total number of RWY/TWY conflict points	.021	.015	2.057	1	.152	1.021
	Total number of TWY/TWY conflict points	.006	.008	.615	1	.433	1.006
	Constant	-1.484	.366	16.441	1	.000	.227

R^2 = .060 (Hosmer&Lemeshow), .080 (Cox&Snell), .107 (Nagelkerke). Model X^2 = 23.759, p < .001.

Table 83: Parameter estimates airport characteristics level 3 (RWY/RWY conflict points) vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 2 RWY/RWY conflict points	.011	.828	.000	1	.989	1.011
	Number of type 3 RWY/RWY conflict points	.106	.661	.026	1	.873	1.111
	Number of type 4 RWY/RWY conflict points	.094	.122	.600	1	.439	1.099
	Constant	-.106	.147	.514	1	.474	.900

R^2 = .006 (Hosmer&Lemeshow), .009 (Cox&Snell), .012 (Nagelkerke). Model X^2 = 2.632, p > .05.

Table 84: Parameter estimates airport characteristics level 3 (RWY / TWY conflict points) vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 2 RWY/TWY conflict points	-.103	.078	1.760	1	.185	.902
	Number of type 3 RWY/TWY conflict points	.109	.033	11.054	1	.001	1.115
	Number of type 4 RWY/TWY conflict points	-.048	.029	2.759	1	.097	.953
	Number of type 5 RWY/TWY conflict points	-.017	.124	.019	1	.891	.983
	Number of type 6 RWY/TWY conflict points	.558	.335	2.772	1	.096	1.748
	Constant	-1.355	.374	13.112	1	.000	.258

R^2 = .066 (Hosmer&Lemeshow), .088 (Cox&Snell), .117 (Nagelkerke). Model X^2 = 26.173, p < .001.

Table 85: Parameter estimates airport characteristics level 3 (TWY / TWY conflict points) vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 2 TWY/TWY conflict points	.081	.053	2.350	1	.125	1.084
	Number of type 3 TWY/TWY conflict points	-.007	.008	.935	1	.334	.993
	Number of type 4 TWY/TWY conflict points	.061	.028	4.706	1	.030	1.063
	Number of type 5 TWY/TWY conflict points	-.026	.062	.168	1	.682	.975
	Number of type 6 TWY/TWY conflict points	.239	.432	.305	1	.581	1.269
	Constant	-1.551	.479	10.466	1	.001	.212

R^2 = .054 (Hosmer&Lemeshow), .072 (Cox&Snell), .096 (Nagelkerke). Model X^2 = 21.313, p < .001.

Table 86: Parameter estimates airport characteristics level 3 (type 4 conflict points) vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 4 RWY/RWY conflict points	.230	.078	8.648	1	.003	1.258
	Number of type 4 RWY/TWY conflict points	-.020	.023	.725	1	.395	.981
	Number of type 4 TWY/TWY conflict points	.077	.024	10.532	1	.001	1.080
	Constant	-1.411	.316	19.983	1	.000	.244

R^2 = .068 (Hosmer&Lemeshow), .091 (Cox&Snell), .121 (Nagelkerke). Model X^2 = 26.955, p < .001.

To summarise, the analysis proved that airport characteristics do have an impact on the severity of runway incursions. When testing the variables individually the majority of airport characteristics were found to make a significant contribution to the prediction of severity. Whilst evidence for the impact of individual characteristics on severity was found, it was also shown that airports are too different in their characteristics and that therefore such data should not be aggregated. Since it was not possible to categorise airports in terms of complexity, the individual elements of surface geometry were analysed in more detail. This identified the number of runways and their overall number of conflict points as significant predictors. Also, the impact of particular intersections between runways and / or taxiways was highlighted.

Overall, it can be concluded that it is not the complexity of an airport in general which influences the severity of occurrences; rather, it is only certain elements of an airport's geometry that seem to create a problem and this has implications for further analysis. The

next section looks at interactions between the system components and analyses for example, how the airport physical characteristics influence the operations of human operators. First, however, the human interactions are modelled.

11.2.3 Analysis of Interactions

11.2.3.1 Interaction of Human-Related Factors

Often, occurrence reports allow the extraction of more than one causal factor from the narrative. This can be a combination of factors caused by a single stakeholder (e.g. a pilot made several mistakes) or a combination of factors between different parties (e.g. pilot – ATC interaction). Therefore, it is analysed whether a combination of causal factors between different parties compared to a combination of causal factors caused by a single stakeholder influence the severity of occurrences. The data showed an association between stakeholder interactions and severity levels (X^2 (1) = 6.960, p < .05) and the graphical assessment (Figure 141) concluded that almost 80.0% of occurrences that showed an interaction between at least two parties were classified as high severity Cat C.

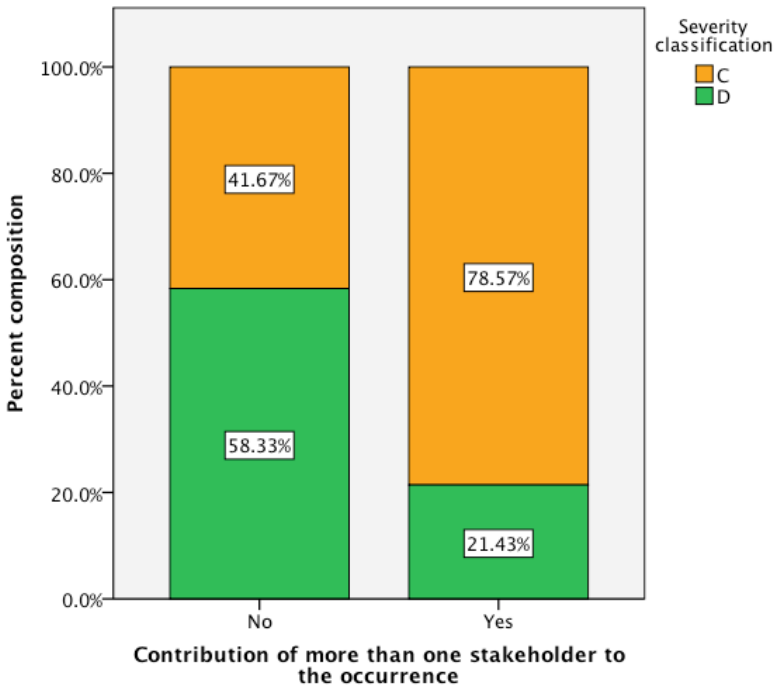


Figure 141: Stakeholder interactions across severity categories

Binomial logistic regression analysis further revealed that, in fact, occurrences caused by a combination of at least two parties are 5.13 times more likely to be high severity than occurrences caused by a single stakeholder. Table 87 contains the parameter estimates.

Table 87: Parameter estimates stakeholder interaction vs. severity

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	At least two stakeholders interacting	1.636	.675	5.875	1	.015	5.133
	Constant	-.336	.177	3.632	1	.050	.0714

R^2 = .018 (Hosmer&Lemeshow), .048 (Cox&Snell), .064 (Nagelkerke). Model X^2 = 7.199, p < .05.
The DV reference category is Severity Cat D (Low) and the IV reference category is occurrence caused by only one stakeholder.

The most frequent factor combination leading to high severity was an ATC and pilot interaction that involved communication errors. A total of 42.0% of Cat C occurrences which showed stakeholder interaction showed pilot – ATC communication related errors, and all of these were related to the readback. Out of all occurrences, 52.0% of incursions which showed a stakeholder interaction showed communication-related errors and 40.0% included readback errors. When modelling the system, communication had been identified as the interface between the stakeholders and the current analysis showed that this interface is vulnerable and prone to errors.

11.2.3.2 Influence of Airport Characteristics on Surface Operations

After having analysed the stakeholder interactions, the following section tries to explain how the airport influences the human operations resulting in an accident / incident.

- **The impact of airports on causal factors**

The impact of the airport as a whole on the occurrence of causal factors was analysed. Using contingency tables, no pattern could be identified with the causal factors being found to occur across all airports. Appendix X Table 9 shows the distribution of causal factors (level 3) across airports. The same analysis was conducted at the factors level, with similar findings. The airport as a whole, therefore, cannot explain the occurrence of causal factors.

- **The impact of airport surface geometry on causal factors (aggregated level)**

Subsequently, multinomial logistic regression was employed to analyse whether the design of the airport surface (i.e. geometry) influences the causal factors (level 1). Although most models showed a significant improvement to the baseline model, their overall model fit was poor, leading to the conclusion that geometric characteristics of the manoeuvring area are not a significant predictor for the causes underlying runway incursions. Appendix X Table 10 summarises the results. The estimates are based on an analysis of the whole dataset.

- **The impact of airport surface geometry on pilots, ATC and V/PD**

Whilst airport geometric characteristics may not influence the total of causal factors, they might influence particular operations and predict their associated failures. Thus, further analysis split the factors into pilot, ATC and V/PD-related and repeated the analysis for each stakeholder individually. Again, airport characteristics did not significantly predict the causal factors (level 3), with the results summarised in Appendix X Table 10.

- **Mapping causal factors to airport surface geometry**

Although the last part of the analysis split the causal factors by stakeholder operations the data might still be too aggregated. Further analysis at the factor-level, therefore, related individual runway incursions and their associated causes to the specific locations at the airports where they occurred.

For instance, the descriptive narrative of an occurrence report stated: "An a/c, next in line for departure, taxied into position on RWY X at approach end without clearance. No conflicts reported." The analysis revealed that this occurrence happened at the approach end of a runway at a type 3 RWY / TWY conflict point as shown in Figure 142.

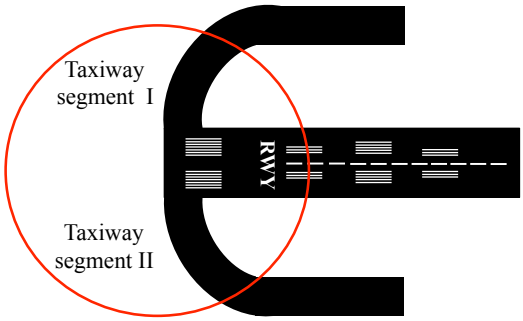


Figure 142: Runway approach end type 3 RWY / TWY conflict point

This detailed analysis assigned each causal factor a corresponding occurrence location and Table 88 summarises the identified spots. All incidents occurred at a runway or a runway intersection, i.e. RWY / TWY or RWY / RWY conflict point, and the analysis revealed causal factors associated to the following locations:

- ATC factors related to only runways (e.g. ATC cleared an aircraft to start its take-off roll while another aircraft still occupied the runway);
- ATC factors related to RWY / TWY conflict points, in particular type 3 and 4 (e.g. ATC cleared an aircraft to cross a runway whilst a second aircraft was on final approach);
- V/PD factors related to runways and all types of RWY / TWY conflict points (e.g. V/PD entering runways without authorisation in various locations); and
- Pilot factors related predominantly to type 3 and 4 RWY / TWY intersections (e.g. pilot crossing a runway at the approach end in a type 3 RWY / TWY conflict point, or pilot crossing in the middle of a runway in a type 4 RWY / TWY conflict point; similarly, hold lines can be crossed at the approach end of a runway before line up or during taxiing when the pilot was instructed to hold short of a runway)

The most critical operations at the analysed airports were related to the stochastic interface of the location, and, in particular, runway crossings. These were either unauthorised crossings initiated by the pilot, or ATC authorised crossings that were planned too tightly. In addition, take-offs and landings without clearance were identified that were particularly crucial at intersecting runways, or in situations where another aircraft crossed the active runway. The airports that have intersecting runways (i.e. RWY / RWY conflict points) showed problems associated to those, for example, two aircraft land / start the take-off roll at the same time at an intersecting pair of runways. Other common failures included taxi errors at RWY / RWY conflict points.

Overall, the runway incursions occurred most frequently at the runways, type 3 and 4 RWY / TWY conflict points and type 4 RWY / RWY conflict points, which corresponds to the airport characteristics identified in section 11.2.2.4 as best predictors for the severity of runway incursions. In contrast to the analyses conducted before, the final part built up evidence that there is a link between the geometric characteristics of an airport and the causes for surface accidents and incidents. This suggests that in order to understand occurrences better data should not be aggregated, but analysed in its elements.

Associations between the causal factors and the extracted occurrence locations could not be computed due to a large number of cells (i.e. more than 20.0%) in the contingency table that showed an expected count of less than five. With a high percentage of zero-frequency cells the data was also not suitable to model the impact of the location on the causal factors using multinomial logistic regression.

To summarise, the analysis showed that certain causal factors happen in particular locations at airports that are associated to high-severity occurrences. Why these causal factors happen there, however, cannot be explained since the causal factors are not attributed adequately. As the prior analysis showed, apart from ATC factors, the data captures predominantly factors that are more representative of an 'outcome' rather than a cause. Hence, the real causes of the incidents are not explained. That is, airport surface operations can fail in many ways before they lead to an incident that occurs in a certain location, but this information is not captured through the reporting system. Overall, the analysis indicates a link between the characteristics of an airport and the causes underlying runway incursions, however, the data is not good enough to model this link.

Table 88: Causal factors per airport location

Causal factor	Runway	Type 2 RWY / TWY	Type 3 RWY / RWY	Type 3 RWY / TWY	Type 4 RWY / RWY	Type 4 RWY / TWY	Type 4 TWY / TWY	Type 5 RWY / TWY	Type 6 RWY / TWY	Unknown type RWY / TWY	Total
Pilot entering a runway without clearance	3	5	2	16	4	38	1	5	0	6	80
Pilot not stopping at the required position (e.g. stop bar)	0	17	2	4	1	21	1	0	0	3	49
V/PD entering a runway without clearance	4	1	3	11	3	13	0	0	0	1	36
Pilot crossing the hold line in front of a runway	2	1	0	7	0	11	2	9	0	0	32
Pilot entering a taxiway without clearance / taxi error	1	0	0	8	1	11	7	1	0	2	31
ATC misjudgement of timings that lead to a situation that was too tight	5	0	0	2	3	1	1	1	0	0	13
Pilot take-off without clearance	4	0	0	3	0	3	0	0	0	0	10
V/PD entering a taxiway without clearance	3	0	1	0	0	3	0	0	1	1	9
ATC issued conflicting clearances	2	0	0	2	2	2	0	0	0	0	8
Pilot landing without clearance	4	0	0	0	0	0	0	0	0	0	4
Total	28	24	8	53	14	103	12	16	1	13	272

11.3 Discussion

This chapter proposed a systematic framework for the analysis of airport surface safety occurrences and demonstrated its application using the example of the U.S. FAA RI database. Within this framework the system architecture was dissected into its elements and the impact and interactions of each of the system components on safety modelled. This allowed a better understanding of the causal factors and their consequences compared to traditional accident / incident analysis methods. The main findings are summarised below.

- **Relationship between causal factors and severity**

The FAA reporting system is biased by the stakeholder perspective it reflects (i.e. ANSP) and, as a consequence, the data is characterised by an inadequate attribution of causes for pilot and V/PD human-related factors. Therefore, the data allows pilot and V/PD factors to be modelled only on a high-level before they became too generic as a result of an inadequate attribution of causes during the reporting process.

Only ATC-related factors are captured in greater detail and refer to concrete examples of deviations of ATC operations. In general ATC's contribution to high-severity occurrences stands out with an overrepresentation of ATC human-related factors in Cat A, B, and C. However, as the FAA RI database cannot capture pilot and V/PD factors in sufficient detail, the critical role of ATC in causing high severity incursions might be a result of the biased and inadequate reporting. Nonetheless, risk mitigation measures should address ATC.

The analysis identified furthermore that a failure in the interaction of at least two stakeholders increases the odds of having high-severity runway incursions; in particular, the interface of communication is vulnerable. Communication-related factors had also been mentioned most frequently in the literature as causes for incursions and should therefore be addressed with priority. This was confirmed by 20 U.S. pilots (see interviews conducted in Chapter 7 section 7.2.6) who referred to runway configurations (i.e. crossings) that require too much communication between pilots and ATC as one of the main causes for incursions.

Finally, the analysis showed that high-severity runway incursions do not occur for unique reasons and that similar causal factors are reported across all severity categories. The factors differ in their frequencies, however indicating that safety risk mitigation strategies based on frequency analyses alone could channel risk mitigation efforts ineffectively.

- **Relationship between airport characteristics and severity**

The analysis showed for the first time that airport characteristics influence the severity of occurrences. When testing the variables individually the majority of airport characteristics were found to make a significant contribution to the prediction of severity and the airport characteristics that predicted severity best are the number of runways, taxiway segments, type 3 RWY / TWY conflict points, and type 4 TWY / TWY conflict points. It was further shown that it is the individual characteristics of an airport that influence the severity of occurrences rather than the total complexity of an airport. When modelling the elements of the airport surface geometry the number of runways, RWY / RWY conflict points, type 3 RWY / TWY conflict points, and type 4 TWY / TWY conflict points were the most significant predictors for severity. Therefore, safety mitigation strategies should focus on those critical airport design elements and possible risk mitigation measures are discussed in section 11.4.

- **Relationship between airport characteristics and causal factors**

Chapter 11 showed that an analysis of safety and airport data at an aggregated level is ineffective: the causal factors are not associated with the airports and also the individual airport characteristics are not significant predictors for the causal factors. A more detailed analysis, however, could reveal the locations at which the runway incursions predominantly happened (runway, type 4 RWY / RWY conflict point, type 3 and 4 RWY / TWY conflict points). These reflect the stochastic interface of the location. Therefore, the analyses build up evidence that there is a link between airport surface geometry and causal factors. However, due to an inadequate attribution of causal factors and a large amount of missing information this link cannot be modelled. Hence, organisations should invest into the collection of high quality data to support further statistical modelling.

To summarise, the analyses showed that the odds of having a high-severity occurrence increase at particular airport locations. In addition, the causal factors that are more likely to lead to a high-severity occurrence than others were identified. Finally, it was shown that these causal factors occur in the locations that are associated with high severity occurrences. Why these causal factors happen there, however, cannot be explained due to inadequate reporting practices and a resulting inadequate attribution of causal factors.

11.4 Recommendations

Based upon these results, the following paragraphs outline recommendations for the mitigation of the safety risk of runway incursions, the collection of safety data, as well as the modelling of such data.

To mitigate runway incursions the critical role of ATC needs to be addressed through continuous training. In addition, the analysis highlighted that the interface between ATC and pilots is vulnerable and, therefore, problems in the communication process (e.g. readbacks) between pilots and ATC need to be addressed and continuously trained for.

Besides human factors, the analysis also identified the geometric characteristics of the airport surface that increase the odds of having high-severity occurrences. To reduce the risk of high-severity runway incursions future airport design should avoid RWY / RWY conflict points and limit the number of type 3 and 4 RWY / TWY conflict points. Existing airports with a high number of RWY / RWY and RWY / TWY conflict points should evaluate alternative operating scenarios, in particular to avoid runway crossings.

Acknowledging that changes in the operating scenarios of existing airports may lead to time and cost inefficiencies, the results support the case for new technologies, such as Runway Status Lights (RWSL) and the Final Approach Runway Occupancy Signal (FAROS), which have been discussed in the literature review. RWSL identify any possible conflict with other surface traffic and warn pilots when it is unsafe to cross, enter or begin take-off on a runway, via a series of red lights embedded in the pavement. FAROS provides a notification to pilots on final approach that their runway for landing is occupied and unsafe for landing through a flashing of the PAPI lights. In addition, alternative design options, such as perimeter taxiways that allow aircraft to taxi around the approach end of a

runway and avoid the crossing of active runways, would help to reduce the potential for a runway incursion (Federal Aviation Administration, 2008b).

To improve the collection of quality safety data the following recommendations are formulated. The analysis presented in this chapter is limited to runway incursions only and a large number of surface incidents (i.e. taxiway incursions) had to be excluded since no severity assessments were conducted for these incidents. In order to get a fuller understanding of surface safety both runway and taxiway incursions must be analysed and, therefore, a severity assessment is required for all of them. This relates back to a lack in the fundamentals of surface safety and data collection and reporting practices. Furthermore, incursions need to be investigated more specifically in order to assign the causal factors adequately as only an adequate attribution of causes would support a dissection of the system into its elements and allow for detailed modelling of each of the system's components. To realise the collection of higher-quality data, the reporting system would benefit from the multi-stakeholder approach proposed in this thesis.

The analysis of airport surface safety and its modelling should follow SMS principles which require the analysis of all system components and their interactions. Any analysis, therefore, should use the system architecture as its reference, dissect the system and analyse each of its components as well as their interactions following a dedicated modelling strategy (as outlined in section 11.1.4). Dissecting the problem allows the identification of the critical issues for each system components that would not be determined using aggregated data. In order to do this, the importance of collecting high-quality data is once again stressed.

The aim of this chapter was the development of a systematic analysis framework for airport surface safety occurrences and the demonstration of its methodology. Proposing a framework (as outlined in Figure 131) and applying it to a sample of 283 runway incursions from 19 airports have achieved this, however, the analysis is limited by the small sample size of airports and should not be generalised. In addition, the analysis is restricted by the quality of the reported data and, therefore, future work should evaluate the modelling capabilities of databases with better DQIs that are able to capture the causal factors in greater detail.

To summarise this research, the next section presents the overall framework for a holistic airport surface safety management that has been developed throughout this thesis.

11.5 Framework for a Holistic Airport Safety Management

To control safety risks, airports are required to have a dedicated Safety Management System (SMS). Although an international legislative framework exists, Chapter 4 showed that national regulations for airport SMS are still under development. Therefore, little practical guidance for its deployment and implementation is currently available.

To assist airports and other aviation stakeholder with the development and implementation of SMS, this thesis developed a framework for a holistic airport safety management. The framework is shown in Figure 143. The analyses to be completed in each step are shown in red and the outcomes after each step are highlighted in blue, whilst the data inputs are shown in green.

An integrated safety assessment of airport surface operations requires a fundamental understanding of an airport's static architecture and the process of its operations. A prerequisite for the development of an airport SMS is therefore, the modelling of the airport surface system architecture in its components (stakeholders, physical infrastructure) and their interdependencies.

The system's assessment for safety risks starts with identifying its hazards. Therefore, the failure modes of the process of surface operations and their underlying causal factors must be analysed in detail. To determine the causal factors safety data reflecting the perspectives of all relevant stakeholders in the context of surface safety (airport operator, airline, ANSP, ground handling company, regulator) needs to be analysed and a dedicated data pre-processing strategy must assure the validity of the collected data. In particular, the data needs to be assessed for its internal validity, external validity, and for the reporting levels. If required, further methodologies should be exploited to gain a more detailed insight into the causal factors for certain fuzzy areas that cannot be well defined through safety data alone. Validity and reliability checks throughout the analyses ensure the framework's overall robustness.

To quantify the safety risks of the consequences of the hazards, the airport surface system architecture needs to be dissected into its components. The relationship between accidents and incidents and their underlying causal factors is modelled for each of the components individually and subsequently for their interactions. This allows resources to be directed more effectively towards the development of effective solutions for airport surface safety analysis and mitigation.

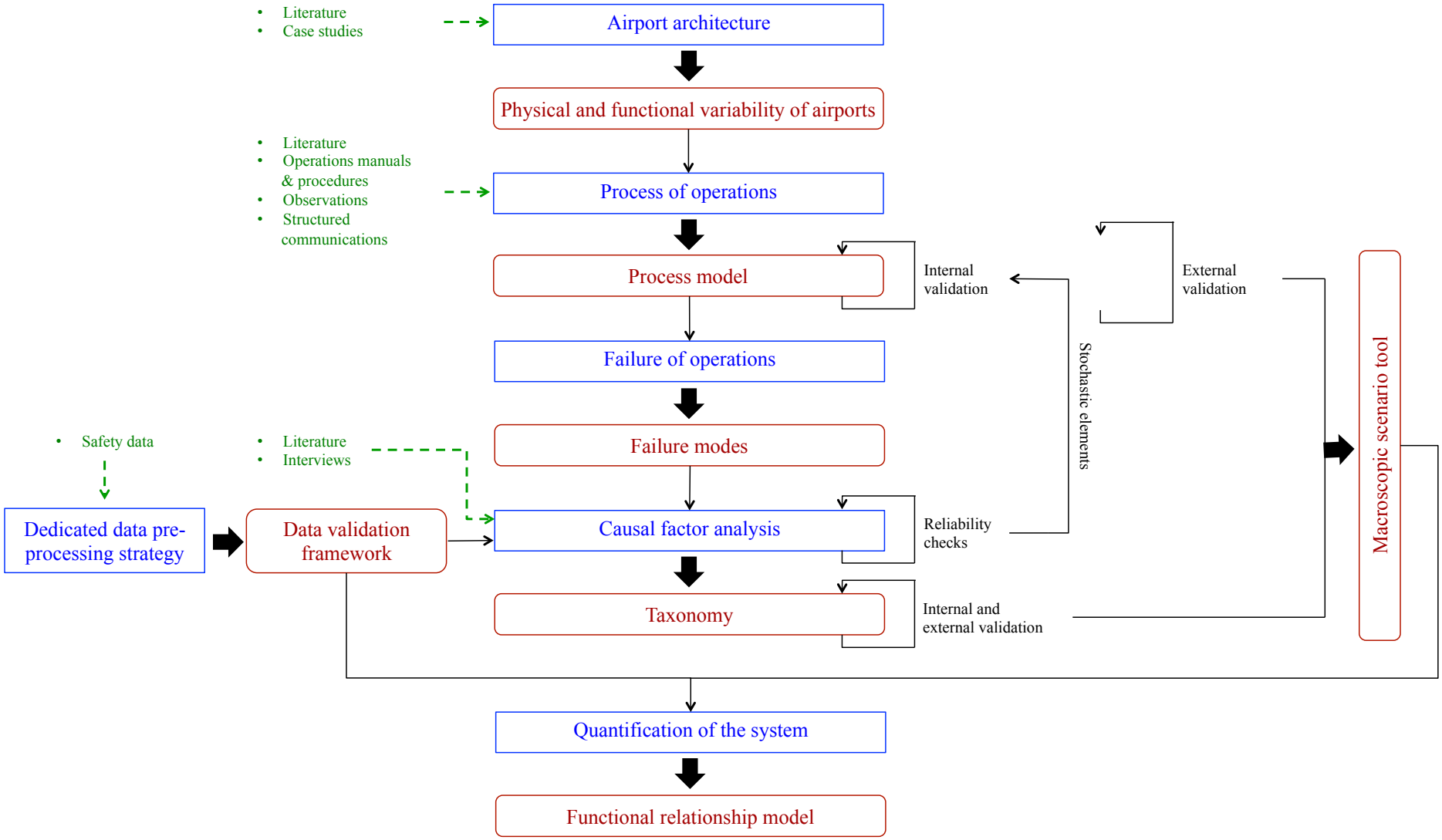


Figure 143: Framework for a holistic airport safety management

The framework (Figure 143) for a holistic airport surface safety management is applicable and, therefore, recommended to all relevant aviation stakeholders that are involved in surface operations.

11.6 Summary

This chapter has quantified the airport surface system by proposing a systematic framework for the analysis of occurrences. The framework is based on the system architecture and models the functional relationship between accidents / incidents and their underlying causal factors by dissecting the system into its elements and analysing each component and their interactions separately. The dissection allows the relationships between the system characteristics (i.e. airport characteristics), system failures (i.e. causal factors), and their consequences (i.e. runway incursions expressed in terms of their severity), to be modelled, and this fulfils the seventh research objective. The proposed analysis goes beyond traditional approaches for accident / incident analysis and, therefore, allows risk mitigation efforts to be channelled more effectively. It is a robust framework for the analysis of safety data and, therefore, supports the risk management function of SMS. The framework can be applied to any other aviation safety database, providing that the causes of accidents and incidents are captured in sufficient detail and that a sensible severity classification has been applied. In addition, limitations in current data collection practices and reporting systems were identified and recommendations for their improvement given.

Finally, the chapter concluded with the presentation of the overall framework for a holistic airport safety management as developed throughout this thesis.

12 Discussion and Future Work

This thesis has investigated the problem of airport surface safety in an integrated manner. This final chapter presents the main findings of the research. The approach taken is to address each of the research objectives formulated in Chapter 1 and to present the corresponding findings and main contributions of this thesis. The chapter concludes with a series of ideas for future work and a list of publications from this thesis.

12.1 Revisiting the Research Objectives

The aim and objectives of this thesis are re-stated to facilitate the full understanding and impact of the main findings of this thesis. The aim of this thesis was to develop a framework for a holistic airport surface safety management and Chapter 1 defined a set of seven research objectives for this thesis. These are to:

1. Model the physical and functional architecture of airports and define its variability.
2. Develop a 4-dimensional (4D) process model of airport surface operations.
3. Provide a systematic literature review to highlight the limitations of current approaches and potential barriers to the effective mitigation of airport surface accidents / incidents.
4. Develop a data validation framework.
5. Determine the causal factors underlying airport surface accidents / incidents.

6. Develop a macroscopic scenario tool to support the safety management of airport surface operations.
7. Propose a systematic framework to assess the functional relationship between airport surface accidents / incidents and their underlying causal factors.

The next section summarises the main findings and contributions of this thesis.

12.2 Conclusions

The International Civil Aviation Organisation (ICAO) requires airports to implement a SMS. Although the international legislative framework exists, national regulations are still under development, and therefore, little guidance available how to effectively analyse and mitigate safety risks. To overcome the lack of standards in the industry this thesis proposed a framework for the development and implementation of a airport SMS. The framework provides detailed guidance for aviation stakeholders for SMS development starting from the description of the airport system to its quantification in terms of safety risks.

With the framework this thesis delivered a SMS standard for airports. The standard exceeds international requirements by standardizing the two SMS core functions (safety risk management and safety assurance) and integrating safety-relevant information across all relevant stakeholders. Once implemented, the integrated SMS processes allow the utilization of shared data for the safety risk management process of all stakeholders. This allows a more effective use of safety information and provides an improved overview on, and prediction of safety risks and ultimately improves the safety level of airports and their stakeholders. The particular contributions to the state-of-knowledge are summarised below.

12.2.1 Model of the Functional Architecture of Airports

A model of the static airport architecture has been developed and the physical and functional variability in airports defined. One main conclusion was drawn: whilst the physical and functional architecture of airports in terms of its components, activities, and main stakeholders is invariable, the implementation of these components and activities varies (Chapter 2).

12.2.2 Development of a 4D Process Model

The process of surface operations has been modelled and integrated in a high-level architecture defining the overall airport surface system. This state-of-the-art model presents the first integrated architecture of surface operations showing the interactions between the physical infrastructure, the relevant stakeholders and external influences. The system architecture is recommended as baseline model to guide the development of SMS for airports (Chapter 3).

12.2.3 Review of the Literature and Current Airport Surface Safety Analysis and Mitigation Practices

A state-of-the art literature review on airport surface safety has been presented. The review consolidated the available literature of the different occurrence types and identified that current approaches to airport surface safety analysis and risk mitigation lack integration and do not comply with the requirements of a SMS. Therefore, data requirements for the development of SMS have been derived from the literature and these are recommended to all aviation stakeholders (Chapters 4 and 5).

12.2.4 Development of a Data Validation Framework

A reference data set, combining a total of twelve safety databases that reflect the perspectives of all relevant stakeholders (airport operators, airlines, ANSPs, ground handling companies and regulators) has been collected. In addition, a novel data quality assessment framework that accounts for the specific characteristics of airport surface safety data has been developed. This framework gives a robust indication of the quality of a database through a combination of internal validation, external validation, and an analysis of the reporting level. It is recommended for data quality assessments of aviation safety databases (Chapter 6).

12.2.5 Determination of Causal Factors

A new taxonomy that provides a common industry language for the causal factors of airport surface safety occurrences has been developed. The taxonomy provides a state-of-the-art tool to support the data analysis function in the context of SMS. Its unique feature is its integration and applicability to all relevant aviation stakeholders in the context of surface safety and, therefore, it is recommended for the operational safety risk management of all aviation stakeholders (Chapters 5 to 9).

12.2.6 Development of a Macroscopic Scenario Tool

A macroscopic scenario tool to support SMS change management has been developed and its use is twofold. The tool allows the evaluation of the impact of changes in the airport surface system architecture to guide further analysis. Furthermore, it guides safety assessments that may be required as a result of a changing system (Chapter 9).

12.2.7 Functional Analysis of Airport Surface Safety

A systematic analysis framework to model the functional relationship between airport surface accidents / incidents and their underlying causal factors has been proposed. The advantages of using this framework are threefold. Firstly, it is a systematic framework illustrating how to dissect the airport surface system architecture and how to analyse its components and interactions. Secondly, the model can assess the safety performance of airport surface operations and thus help to understand where and how the system can fail as a result of certain conditions. Finally, it enables a more thorough analysis and the identification of statistically significant factors and interactions to help the decision making process for proposing safety recommendations. The framework is recommended to the aviation stakeholders for quantification of the safety risks associated to their operations (Chapter 11).

12.3 Future Work

The findings suggest a number of directions for future research. These include:

- The functional relationship between airport surface accidents / incidents and their underlying causal factors has been modelled using a sample of 19 U.S. airports. In order to generalise the findings, the analysis should be extended and a larger sample size considered. In addition, the modelling capabilities of other databases with a better DQI should be assessed and compared to the current findings.
- This work proposed a framework for a holistic approach to airport safety management. The idea is to combine all information available from the relevant aviation stakeholders in order to allow for an integrated analysis of surface safety. Due to data quality considerations, however, an aggregation of safety data was not possible at this stage. To evaluate the effectiveness of the proposed concept, it should be implemented in a case study. That is, all aviation stakeholders of one country should collect safety data to common standards that include standardised definitions and data collection and investigation processes. Using the tools developed in this thesis (i.e. taxonomy, systematic analysis framework) it will then be possible to analyse the collected data and to evaluate the effectiveness of the proposed multi-stakeholder approach.
- The work presented in this thesis is based predominantly on historical data (accident and incident data) that depict so called lagging indicators. As was noted in Chapter 4, a SMS should combine reactive, proactive and predictive methods. Therefore, future work should evaluate the transferability of the proposed framework to leading indicators that are not occurrence based (e.g. monitoring of daily operations to identify abnormalities, safety culture of an organisation).
- Although, ideally, any situation that may or may not directly challenge the safety of the system should be collected, future research should address the cost-benefits of safety data collection. This could take the form of, for instance, the development of a data collection system in reference to severity levels, in particular, when including leading indicators. Similarly, the interdependencies between safety and other Key Performance Areas (KPAs) should be assessed to balance the associated Key Performance Indicators (KPIs) with acceptable safety risks.

- The analysis presented in this thesis is limited by excluding the Asian market despite its significance in terms of global air traffic. Therefore, future work should address Asia once the concept of a just culture has been established in this region. The tools and methodologies for an airport SMS based on sources of good quality safety data have been developed in this thesis. Similarly, developing regions such as Africa or South America could benefit from the implementation of the analysis framework proposed in this work.
- Finally, the potential for the proposed framework for a holistic approach to safety management to be transferred to other areas of aviation safety that suffer from non-integrated practices (e.g. ground handling) and other transport modes (e.g. the railway system) should be assessed.

12.4 Publications Relating to this Work

The following publications have been produced in support of this research.

12.4.1 Publication Format: Journal – Published

Wilke, S. and Majumdar, A. (2012). Critical factors underlying airport surface accidents and incidents: A holistic taxonomy. *Journal of Airport Management*, 6(2), pp. 170-190.

Wilke, S., Majumdar, A. and Ochieng, W. (2012). Holistic approach towards airport surface safety. *Transportation Research Record - Aviation 2012*, Vol:2300, pp.1-12.

Wilke, S., Majumdar, A. and Ochieng, W. (2013). Airport surface operations: A holistic framework for operations modeling and risk management. *Safety Science*, 63 (2014), pp. 18-33. http://dx.doi.org/10.1016/j.ssci.2013.10.015

Wilke, S., Majumdar, A. and Ochieng, W. (2013). A framework for assessing the quality of aviation safety databases. *Safety Science*, 63 (2014), pp. 133-145. http://dx.doi.org/10.1016/j.ssci.2013.11.005

12.4.2 Publication Format: Conference Proceedings – Published

Wilke, S., Majumdar, A. and Ochieng, W. (2013). The impact of airport characteristics on airport surface accidents and incidents. Transportation Research Board – 93rd Annual Meeting, Washington, D.C. 12-16 Jan 2014.

Wilke, S., Majumdar, A. and Ochieng, W. (2013). Assessing the safety of airport surface operations: A 4D process model. The 3rd ENRI International Workshop on ATM / CNS (EIWAC), Tokyo 19-22 Feb 2013.

Wilke, S., Majumdar, A. and Ochieng, W. (2012). Assessing the quality of aviation safety databases: An external data validation framework. 5th International Conference on Research in Air Transportation (ICRAT), Berkley 22-25 May 2012.

Wilke, S., Majumdar, A. and Ochieng, W. (2012). A holistic approach towards airport surface safety. Transportation Research Board – 91st Annual Meeting, Washington, D.C. 22-26 Jan 2012.

Wilke, S. and Majumdar, A. (2011). A multi-national causal analysis of airport surface safety occurrences. 11th AIAA Aviation, Technology, Integration, Operations (ATIO) Conference, Virginia Beach 20-22 Sept 2011.

Wilke, S., Majumdar, A. and Ochieng, W. (2011). The potential of automation to improve airport surface safety. 1st International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS), Barcelona 26-27 May 2011.
Award for the best Ph.D. presentation at the 1st ATACCS conference.

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Appendix I: Unified Modelling Language

This appendix introduces the main Unified Modelling Language (UML) diagrams and their features, as outlined in Schmuller (2009) and Figure 1 summarises upfront the corresponding UML notation.

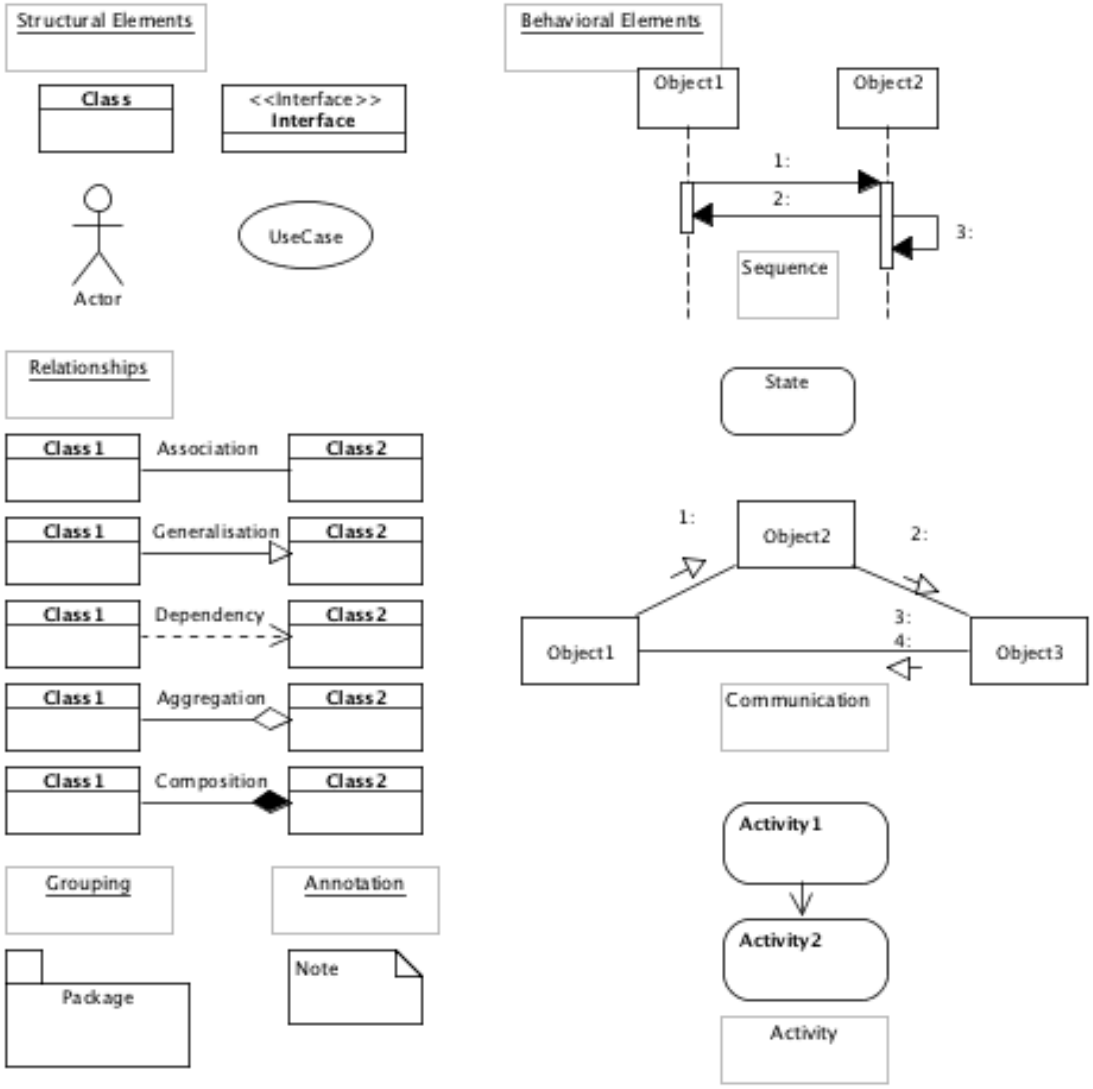


Figure 1: UML notation

1 Structure Diagrams

Structure diagrams set the context for any modelling activity and introduce the basic terminology for the area of interest. In particular, such diagrams show the 'things' that must be present when a system is modelled and include class diagrams, object diagrams, aggregation diagrams, composites and composite structure diagrams, and interface diagrams.

- **Class Diagrams**

The simplest form of a structure diagram is a *class diagram*, which introduces the vocabulary and terminology of the area of interest. A *class* is "a category or group of things that have similar attributes and common behaviours". For example, pilots can be defined as a class with associated attributes and behaviours. *Attributes* describe the properties of the class and a class can have zero, one or multiple attributes. For instance, any pilot in this class has attributes such as name, age, pilot license number, and experience. The behaviour of a class is represented by its operations. An *operation* is an activity a class can do, for instance, pilots could be defined among others by the following operations: 'entering the aircraft', 'preparing the aircraft', and 'flying the aircraft'. Figure 2 shows an example of the UML notation.

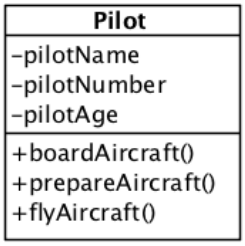


Figure 2: UML class icon

A class consists of objects defined as "instances of a class and have values for each of the class' attributes." In UML an object is represented through a rectangle with the name of the object stated inside and underlined.

Associations, i.e. relationships between the classes, are used to connect classes together conceptually. They are modelled as a line between two classes and the name of the association is shown on top of this line. The roles of the two classes can be added next to the classes. For example, a pilot flies an aircraft on behalf of an airline. The airline employs the pilot and the pilot is employed by the airline (see Figure 3).



Figure 3: Association diagram

A further important concept in class diagrams is that of *generalisation*, which states that information from one class can be transferred to another. For example, *child classes* or *subclasses* can inherit attributes or operations from another *parent class* or *superclass*. If it is known that somebody is a pilot, it is known already that a pilot has a name, age and experience, and part of his / her tasks is to prepare and fly the aircraft. Irrespective of whether the pilot is a cadet pilot, a first officer or a captain, these attributes and operations are always true. Figure 4 summarises the concept of generalisation.

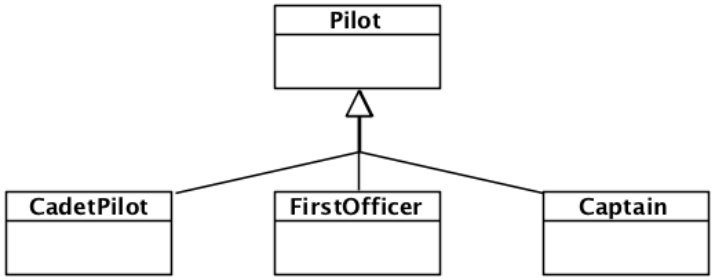


Figure 4: Generalisation diagram

In the case that the operations of one class are used by another class, the relationship is modelled as a *dependency*. For instance, the electronic reporting system for safety occurrences in an airline allows pilots to make a report from the choice of several reporting forms. Among other operations, the computer class is able to display the forms. The form the computer displays is dependent on the pilot's selection. The UML notation in this case is a dashed line with an arrowhead that points at the dependent class (see Figure 5).

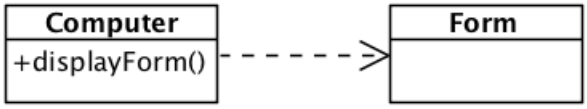


Figure 5: Dependency diagram

- **Object Diagrams**

While class diagrams provide a general overview on classes, objects and their relationships, object diagrams capture the relationship between classes and objects at a given point in time, i.e. they are snapshots used to model specific instances of classes at a specific instant in time.

- **Aggregation Diagrams**

Aggregations are used to model hierarchies of classes. An *aggregation* is defined as "a specific type of association in which one class is a component of another. In an aggregation, the aggregate class can consist of more than one component class." Figure 6 provides an example to illustrate this type of relationship.

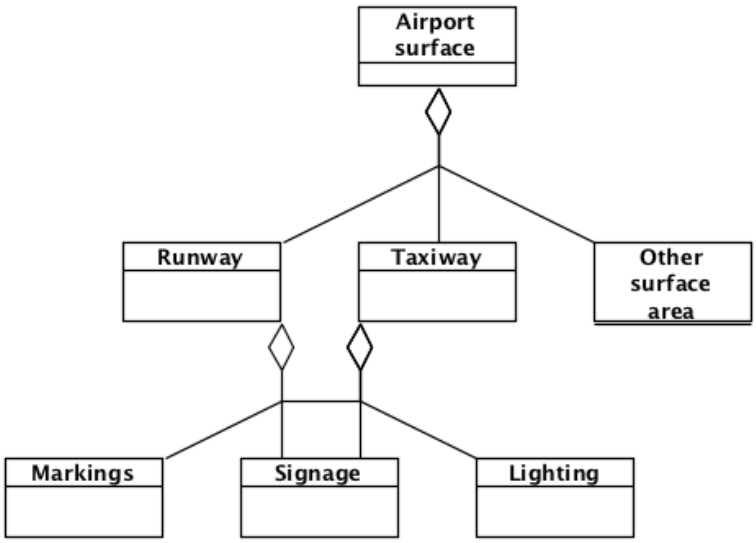


Figure 6: Aggregation diagram

- **Composites and Composite Structure Diagrams**

A *composite* "is a very strong type of aggregation". In an aggregation diagram components can be connected to various components of classes. In composites, on the other hand, each component is a composite that can only belong to just one whole, as shown in Figure 7.

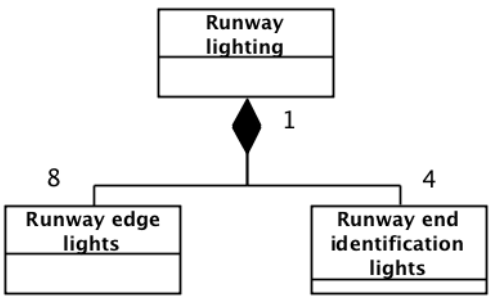


Figure 7: Composite diagram

To represent the internal structure of a class, UML provides the option of using composite structure diagrams. These diagrams show how the components of an object relate to one another.

- **Interfaces**

An *interface* "is a set of operations that specifies some aspects of a class's behaviour, and it is a set of operations a class presents to other classes". For instance, the Flight Management and Guidance System (FMGS) in the cockpit of an aircraft is an interface that allows communication between a pilot and other parties, such as ATC. A possible UML notation for this is shown in Figure 8. Interactions through the interface are modelled as a dependency, because the pilot, for instance, depends on the interface (i.e. FMGS) to get the necessary information.



Figure 8: Interface diagram

2 Use Case Diagrams

Use case diagrams represent the system's behaviour from the user's point of view, vital for system development. For instance, when designing a new aircraft, in order to make sure that it meets the requirements of its users, an initial model is produced for the relevant *use cases*. In a use case analysis the different users of a system (in the current scenario, for instance, the flight crew, cabin crew, passengers, and maintenance engineers) are asked to describe the system and its use from their point of view. Based upon this information, use cases are developed. The idea is to get the system users involved in the early stages of system analysis and design. Use cases can also be useful in contexts other than system design, e.g. to define functional requirements, decision support for choice making, or testing new systems.

The UML notation for a use case model is shown in Figure 9. In this model an actor initiates a use case and receives something of value from it. For example, a passenger uses the aircraft in order to get from Point A to Point B.

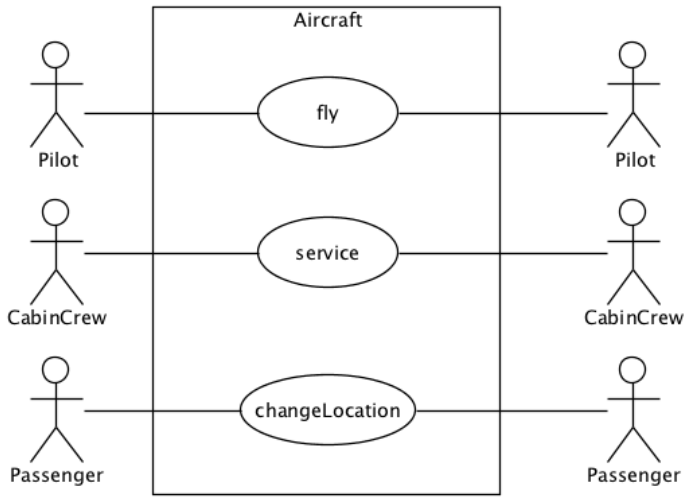


Figure 9: Use case model diagram

3 Behaviour Diagrams

Behaviour diagrams model the behaviour of a system, i.e. they emphasise what happens in a system. State diagrams, sequence diagrams, communication diagrams, and activity diagrams are all behaviour diagrams.

- **State Diagrams**

State diagrams reflect the state of single objects and allow for the modelling of all the changes that objects goes through. Whilst class and object diagrams are used to describe static aspects of a system, state diagrams model the change an object goes through in response to events and time. The UML notation for the state icon is shown in Figure 10.



Figure 10: State diagram

- **Sequence Diagrams**

Sequence diagrams show interactions of objects in time. The idea behind this is that interactions among objects occur in a specified sequence from the beginning to the end.

The UML notation places the objects on the top of the diagram. Extending downwards from each object is a dashed line, called an object's *lifeline*. Along the lifeline is a

rectangle, the *activation*, which represents an execution of an operation by an object. The objects exchange messages, which are represented by arrows. Time in the sequence diagram is represented in the vertical direction, i.e. a message that is closer to the top occurs earlier in time than a message at the bottom of the diagram. Figure 11 contains an example of a UML notation of a sequence diagram in its simplest form.

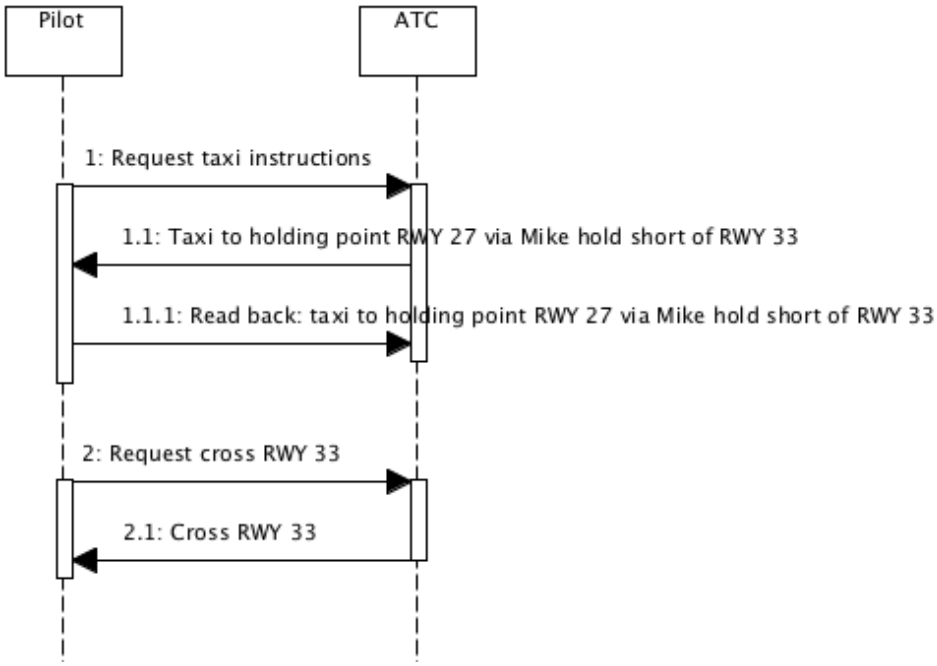


Figure 11: Sequence diagram

- **Communication Diagrams**

Like sequence diagrams, communication diagrams also show how objects interact. The UML notation for communication diagrams shows the objects along with the messages that are exchanged between the objects. Communication diagrams are semantically equivalent to sequence diagrams as they present the same information. Both are *interaction diagrams*. The difference lies in the graphical representation: while sequence diagrams emphasise the order of interactions according to time, communication diagrams emphasise the context and overall organisation of the objects that interact. This means that communication diagrams are organised according to space, i.e. according to the links among the objects. Figure 12 shows an example.

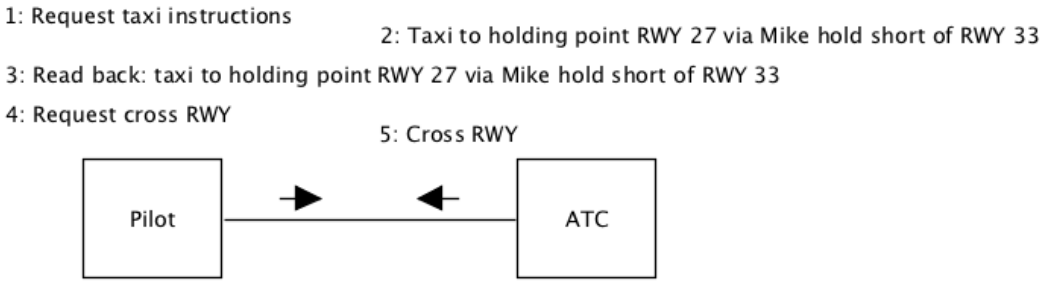


Figure 12: Communication diagram

Communication diagrams are an extension of object diagrams that are snapshots of how objects are linked together in an instant of time. The diagrams show the interactions of objects over time.

- **Activity Diagrams**

Activity diagrams show the steps, i.e. activities, in an operation or process. They provide a simplified view of what happens during an operation. The roles of different actors can be visualised using 'Swinlanes', which dissect the diagram into parallel segments for each actor. Object nodes (i.e. inputs and outputs for an activity) can be specified if needed. Figure 13 shows an example.

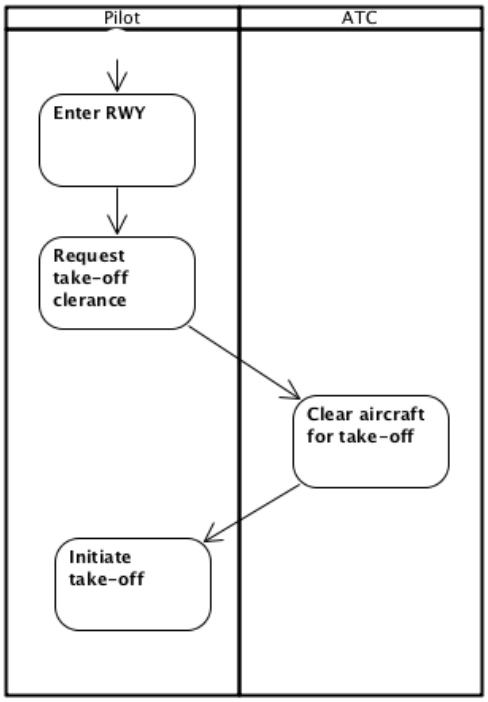


Figure 13: Activity diagram

4 Architectural Diagrams

The last category of UML diagrams, known as architectural diagrams (i.e. component, deployment, and package diagrams), is used to model system architecture.

Component diagrams are used for modelling software components and their interfaces. They contain components, interfaces and relationships and their use is intended specifically to model computer software.

Deployment diagrams are used to model the hardware of computer systems. These diagrams show how pieces of information that a system uses or produces are deployed on system hardware, and how the pieces of hardware connect to one another.

Finally, package diagrams are designed to group elements (e.g. classes, use cases) of a diagram and two possible notations can be used (see Figure 14).

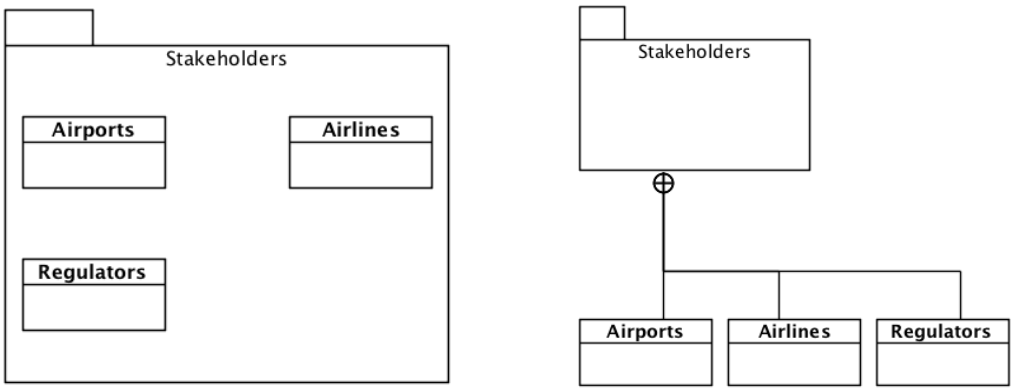


Figure 14: Package diagram

Appendix II: Literature Overview

Table 1: Literature overview on incursions

Reference	Scope	Represented stakeholder viewpoint	Data				Analytical methodology	Outcomes and proposed mitigation measures	Advantages	Disadvantages
			Data source	Time period	Region	Comments on data quality				
Airbus (2004c): Flight operations briefing notes. Preventing runway incursions	•Runway incursions	•Aircraft manufacturer	•Not specified	•Not specified	•Not specified	•Not specified	•Analysis of operational events (not further specified)	•List of causal factors •Guidelines for runway incursion prevention	•Good overview on operational and human factors involved in runway incursions	•Limited scope (i.e. runway-related occurrences only) •Unknown underlying data and methodology •Based upon the findings of a NLR study which is not further specified •V/PD factors are not covered
Airservices Australia (2002): Runway incursion survey	•Runway incursions	•ANSP	•Not data based	•N/A	•Sydney airport	•N/A	•Survey at Sydney airport with pilots (93.0%), ATC (5.0%), V/PD and airport management (2%)	•Most frequently mentioned causal factors	•Insight into the causal factors at an airport level	•Limited scope (i.e. runway-related occurrences only) •Methodology is not specified •Biased sample with 93% of respondents being pilots •Only high-level statistical descriptive analysis
Australian Transport Safety Bureau (2004): Runway incursions: 1997 to 2003	•Runway incursions	•Accident Investigation Board	•ATSB Occurrence Analysis and Safety Investigation System (OASIS) database	•1997-2003	•Austra-lia	•Data quality is not discussed	•Trend analysis •Identification of causal factors	•Causal factors	•Comparison of incursions trends in Australia with those in the U.S. and Europe	•Limited scope (i.e. runway-related occurrences only) •Unknown method for the extraction of causal factors •Only high-level statistical descriptive analysis
Biernbaum and Hagemann (2012): Runway incursion severity risk analysis	•Runway incursions	•Centre for transportation expertise (VOLPE)	•FAA Runway Incursion database •FAA ATQA OE and PD •METAR	•2001-2010	•U.S.	•The quality of the different data	•Summary statistics using association tests (e.g. Chi-Square, Fisher's Exact)	•Models of the impact of -Aircraft factors, -Pilot information, -Airport	•Modelling of runway incursions / robust statistical analysis that goes beyond summary statistics	•Limited scope (i.e. runway-related occurrences only) •The impact of V/PD related factors is not

			•FAA Form 5010 Submissions •FAA ETMSC •Additional data sources for airport characteristics data[17]			sources is discussed, but limited to internal data quality issues (e.g. missing cells) •The accuracy of the data is not discussed	and multinomial logit •Modelling using logistic regression models	characteristics, -Radar, -ATC variables, -Weather variables, and -Others on the severity of runway incursion •Identification of areas for future research	•Identification of factors that impact on the severity of runway incursions •Consideration of a large number of variables	considered •The majority of tested variables represent risk factors (e.g. day vs. night time operations, prevailing weather conditions) and not causal factors (e.g. as extracted from safety data)
Chang and Wong (2012): Human risk factors associated with runway incursions	•Runway incursions	•Academia	•Not data based	•N/A	•Taiwan	•N/A	•Identification of 56 risk factors based on the SHEL[18] model and literature •Questionnaire survey with SMEs to weight the factors •Aggregation of the SME assessments through the analytical hierarchy process (AHP)	•Risk factors •Prioritisation of risk factors	•Robust methodology •SMEs include regulators, safety investigators, and pilots	•Limited scope (i.e. assessment of only pilot-related factors involved in runway incursions) •Risk factors are based upon a literature review and not supported by data analysis
Federal Aviation Administration (2008b, 2009c, 2010d): Annual runway safety report	•Runway incursions	•Regulator / ANSP	•FAA Runway Incursion database	•2007-2009	•U.S.	•Data quality is not discussed	•Trend analysis of runway incursions •Classification of runway incursions into pilot deviation, operational error and V/PD deviations	•Runway incursion trends •Overview on implemented runway incursion prevention measures, and •Overview on mitigation measured to be implemented	•Good overview on the development of runway incursions in the U.S. and safety initiatives	•Limited scope (i.e. only runway-related occurrences) •High-level statistical descriptive analysis •No causal factor analysis

[17] FAA ATQA OE / PD – Air Traffic quality Assurance Operational Error / Pilot Deviation database
METAR – French Meteorologique Aviation Regulier
FAA ETMSC – Enhanced Traffic Management System Counts

[18] SHELL – Software, hardware, environment, liveware

Federal Aviation Administration (2002): Runway incursion airport assessment report	•Runway incursions	•Regulator / ANSP	•Site surveys	•2001-2002	•16 U.S. airports	•N/A	•Site visits of 16 airports with a high runway incursion rate (incl. interviews and meeting with aviation stakeholders) •Identification of causal factors in relation to the airport	•Causal factors •Recommenda-tions for mitigation measures	•Analysis of the contribution of the physical layout and infrastructure to runway incursions	•Purely qualitative approach
Federal Aviation Administration (2007c): Wrong runway departures	•Runway incursions (focus on wrong runway departure)	•Regulator / ANSP	•NTSB •FAA PDS •FAA AIDS •NASA ASRS •FAA NPTRS •FAA OEDS[19]	•1981-2006	•U.S.	•Aggrega-tion of different data bases, but the data are not assessed for their quality and potential for aggrega-tion	•Method for the extraction of causal factors from the data is not specified •Frequency analysis of causal factors	•List of causal factors •Most frequent causal factors •Proposal of safety enhancements	•Evaluation of the effectiveness of various safety mitigation measures	•Limited scope (i.e. wrong runway departures) •Aggregation of data with potential differing qualities •Unknown methodology for the extraction of the causal factors •Only high-level descriptive analysis
Hooey and Foyle (2006): Pilot navigation errors on the airport surface: Identifying contributing factors and mitigating solutions	•Runway incursions (focus on pilot navigation errors)	•Research institute	•Real time simulations with flight crews with 32 2-pilot crews	•N/A	•N/A	•N/A	•Description of the taxi phase •Development of a taxonomy of pilot navigational errors during taxiing •Application of the taxonomy to navigation errors observed during simulation studies of surface	•Taxonomy of pilot navigation errors •Regression model showed no difference between error categories	•Comprehensive insight into pilot behaviour during taxiing •Robust methodology	•Limited scope (i.e. focus on pilot navigation during taxiing)

[19] NTSB – National Transportation Safety Board
FAA PDS – Pilot Deviation System
FAA AIDS – Accident / Incident Data System
NASA ASRS – National Aeronautics and Space Administration Aviation Safety Reporting System
FAA NPTRS – National Program Tracking and Reporting Subsystem
FAA OEDS – Operational Error / Deviation System

							operations •Analysis of simulations using a variety of methods •Frequency analysis of errors •Logistic regression model			
International Civil Aviation Organization (2007): Manual on the prevention of runway incursions	•Runway incursions	•Regulator	•Not data based	•N/A	•N/A	•N/A	•Identification of causal factors based on: The European Organisation for the Safety of Air Navigation (2006) document and a global consensus / state of knowledge from SMEs •Development of recommendations to mitigate runway incursions	•Causal factors •Safety recommendations and best practices to reduce runway incursions	•General recommendations and guidance materials are given (e.g. establishment of prevention programs, incident reporting and data collection) as well as recommendations for all relevant stakeholders (i.e. aircraft operators, pilots, ATC and ANSPs, regulators)	•Limited scope (i.e. only runway-related occurrences) •Based on SME expertise, not supported by data analysis
Kim and Yang (2012): Evaluation of the risk frequency for hazards of runway incursion in Korea	•Runway incursions	•Academia	•Reports of 2 runway incursions in South Korea •Literature •SMEs	•1980-2010	•South Korea	•No discussion on the quality of the different data sources	•Hazard identification based on literature and SME expertise •Weighting of hazards through the analytical hierarchy process (AHP) •Estimation of hazard frequencies based on literature •Fault tree analysis to evaluate the risk frequency of each hazard	•Causal factors •Failure probabilities	•Attempt to model the runway incursion risk in an Asian country that lacks high-quality safety data	•Limited scope (i.e. only runway-related occurrences) •Consideration of only 15 factors •Identification of hazards for a South Korea based on U.S. data is questionable

La Direction Générale de l'Aviation Civile (2007): Etude inscursions sur piste evenèments 2006	•Runway incursions	•Regulator	•DSNA database (ANSP) •ECCAIRS[20]	•2006	•France	•Limita-tions of the data are discussed, but •No formal data quality assessment	•Trend analysis	•Runway incursion development in France (trends) •Causal factors	•National insight	•Limited scope (i.e. only runway-related occurrences) •Very limited list of causal factors •Only high-level statistical descriptive analysis
National Transportation Safety Board (1987): Runway incursions at controlled airports in the United States	•Runway incursions	•Accident Investigation Board	•FAA data	•Not specified	•U.S.	•Data quality is not discussed	•Analysis of safety data •Complementary interviews with ATC, pilots, airport managers, airlines, and FAA	•Causal factors •Recommenda-tions for runway incursion prevention measures	•Combination of research methods (i.e. data analysis, interviews)	•Limited scope (i.e. only runway-related occurrences) •Unknown method for the extraction of causal factors •Focus on ATC and pilot factors, the role of V/PD is not discussed •Purely qualitative analysis
Rogerson and Lambert (2012): Prioritizing risks via several expert perspectives with application to runway safety	•Runway incursions	•Academia	•Based upon SME expertise and judgment	•N/A	•N/A	•SMEs used in the case study are not introduced	•Identification of stakeholders and establishment of a working group •Identification of causal factors based on SME expertise •Assessment of hierarchical factor relationships from each SME •Aggregation of the SME assessments through the analytical hierarchy process (AHP)	•Causal factors •Prioritisation of risks associated to runway incursions	•Addresses the problem that causal factors have different importance for various stakeholders •Consideration of the hierarchical order of causal factors	•Limited scope (i.e. only runway-related occurrences) •Subjective approach reliant on SME judgment
Runway Incursion Joint Safety Analysis	•Runway incursions	•Aviation safety	•NTSB Blue book accident reports	•1990-2000	•U.S.	•Data quality and	•Event sequence analysis (for case	•Recommenda-tions for	•Combination of research methods (i.e.	•Limited scope (i.e. only runway-related

[20] DSNA – Direction des Services de la Navigation Aerienne
ECCAIRS – European Co-Ordination Centre for Accident and Incident Reporting Systems

Team (2000): Results & analysis, August 11, 2000; Runway Incursion Joint Safety Implementation Team (2002): Results and analysis. December 2002		consortia	for accidents •NAIMS for operational errors •NTSB accident database for general aviation accidents •FAA pilot deviation database •Pilot reports from airlines[21]			limitations of the different data sources is discussed	studies) •Development of problem statements (what happened & why) •Causal factors •Development of intervention strategies •Prioritisation of intervention strategies	intervention strategies to reduce the potential of runway incursions in the areas of training, situational awareness, procedures, equipment / facilities, crew resource management, safety culture, communications, and human physiological limitations	case studies, high-level data analysis, expert judgment) •Consideration of commercial and general aviation occurrences •Extensive list of recommendations	occurrences) •The findings from the analysis are not presented (e.g. causal factors) •Focus on incursions involving aircraft (i.e. V/PD related factors and recommendations are not considered)
Stroeve, *et al.* (2009): Systematic accident risk assessment in air traffic by Monte Carlo simulation; Further results published in Stroeve, *et al.* (2011): Contrasting safety assessments of a runway incursion scenario by event sequence analysis versus multi-agent dynamic risk modelling	•Runway incursions	•Research institute	•Technical system specifications •Literature and SMEs •Incident data •Interviews •Measurements from real operations and simulations •Data is not further specified	•Not specified	•Not specified	•Data quality is not discussed	•Modelling a runway incursion scenario as multi-agent system •Quantification of the scenario through Monte Carlo simulation •Validation through additional simulations and interviews with SMEs	•Collision risk model	•Quantitative approach •Modelling of the interactions of all relevant stakeholders	•Limited scope (i.e. assessment of a specific runway incursion scenario) •Underlying data sets are not specified •Collision risk model is only valid for one specific scenario
The European Organisation for the Safety of Air Navigation (2008a): ARIA. Development of a computer based aerodrome runway incursion assessment	•Runway incursions	•Safety organisation	•NLR Air Safety Database •FAA Runway Incursion Database •CADORS •UK CAA MORS[22]	•Not specified	•World-wide	•World-wide incident data is used, but the data are not assessed	•Identification of causal factors based on incident reports •Weighting of causal factors based on their frequency	•List of causal factors •List of incursion counter measures Index that reflects the possibility of having a runway incursion	•Extensive list of causal factors (> 400) •Consideration of runway incursion risk reduction measures	•Limited scope (i.e. only runway-related occurrences) •Literature used to extract the causal factors is not specified •Unknown method for the extraction of

[21] NTSB – National Transportation Safety Board
NAIMS – National Aviation Incident Management System

						for their quality and potential for aggrega-tion	•Identification of incursion counter measures •Weighting of counter measures based on historical occurrence data and SME judgment •Development of an overall risk index •Model validation (correlation f the risk index to incursion rates at 18 airports)			causal factors •Although vehicles are acknowledged V/PD human-related factors are missing entirely •Additive model may not be appropriate for a risk index •Only high-level statistical analysis •Consideration of predominantly regulatory safety data •Aggregation of safety data from various countries with potential differing qualities
The European Organisation for the Safety of Air Navigation, *et al.* (2011): European action plan for the prevention of runway incursions	•Runway incursions	•Industry safety consortium	•Not data based	•N/A	•N/A	•N/A	•Development of recommendations to mitigate runway incursions based on a global consensus / state of knowledge from SMEs	•Safety recommendations and guidance materials for the prevention of runway incursions	•Recommendations and guidance materials are given for all relevant stakeholders (i.e. airports, aircraft operators, ANSPs, regulators, military)	•Limited scope (i.e. only runway-related occurrences) •Based on SME expertise, not supported by data analysis •Predominantly ANSPS participated in the development
The European Organisation for the Safety of Air Navigation Experimental Centre (2006): Main report for the: 2005/2012 integrated risk picture for air traffic management in Europe	•ATM-related accidents (including runway collisions and taxiway collisions)	•Safety organisation	•Large Western commercial jet aircraft (data source not specified) •Flight population data from Boeing •AIRPROX frequencies from the UK AIRPROX Board[23]	•1990-2002	•World-wide	•World-wide accident data is used, but the data are not assessed for their quality and potential for	•Definition of 5 ATM-related accident types •Development of fault trees for each accident type •Development an influence model for common factors	•Causal factors •Failure probabilities for causal factors •Probability of an accident	•Modelling of accident causation scenarios •Quantitative appraoch	•IRP is developed from a ATM perspective and focuses on the impact of ATM on accidents (e.g. V/PD-related factors are not considered, pilot factors are introduced on a very high level) •Aggregation of data with potential differing

[22] NLR – National Aerospace Laboratory of the Netherlands
CADORS – Canadian Civil Aviation Occurrence Reporting System
UK CAA MORS – UK CAA Mandatory Occurrence Reporting Scheme
[23] AIRPROX – Air proximity hazard

			•Flight towards terrain frequencies derived from airline data			aggrega-tion				qualities
Transport Canada (2000): National civil aviation safety committee. Sub-committee on runway incursions. Final report September 14, 2000	•Runway incursions	•Regulator	•Transport Canada CADORS •NAV Canada AOR •Supplemental information from NAV Canada FFBs and Transportation Safety Board ASIS[24]	•1993-2000	•Canada	•Data was validated and evaluated as reliable (the statement is not supported through further explana-tions)	•Trend analysis •Identification of causal factors •Site analysis at the 3 airports with the highest runway incursion risk (meetings with airport officials to discuss problems and mitigation measures)	•List of causal factors •Recommenda-tions for mitigation	•Combination of research methods (i.e. data analysis, site visits)	•Limited scope (i.e. only runway-related occurrences) •Report claims the data has been validated, but no details as to how this was done are given •Unknown methodology for the extraction of the causal factors •Causal factors focus on traffic, airport design, and ATC related factors •Only high-level statistical descriptive analysis
Young and Vlek (2009): An analysis of the causes of airfield incursions attributed to ground vehicles	•Airfield incursions of V/PD	•Academia / Airline	•FAA Air Traffic Quality Assurance (ATQA) database	•1998-2008	•U.S.	•Data quality is not discussed	•Frequency analysis of causal factors	•List of causal factors •Most frequent causal factors •Recommenda-tions for mitigation	•First study looking at runways & taxiways •Identification of causes related to incursions caused by V/PD	•Unknown methodology for the extraction of the causal factors •Only high-level statistical descriptive analysis

[24] CADORS – Transport Canada Civil Aviation Occurrence Reporting System
NAV Canada AOR – Aviation Occurrence Reporting
NAV Canada FFBs – Fact Finding Boards
Transportation Safety Board ASIS –Aviation Safety Information System

Table 2: Literature overview on excursions

Reference	Scope	Represented stakeholder viewpoint	Data				Analytical methodology	Outcomes and proposed mitigation measures	Advantages	Disadvantages
			Data source	Time period	Region	Comments on data quality				
Airbus (2004b): Flight operations briefing notes. Human factors aspects in accidents and incidents	•Runway excursion •Runway overrun	•Aircraft manufacturer	•Not specified	•Not specified	•Not specified	•Not specified	•Analysis of operational events (not further specified)	•List of causal factors •Recommended practices for flight operations	•Good overview on pilot-related human aspects that can underlie excursions	•Unknown underlying definitions, data and methodology •Based upon the findings of a NASA[25] study, which is not further specified
Ale, *et al.* (2009): Causal Model for Air Transport Safety (CATS). Final Report	•Air transport accidents	•Academia	•ICAO ADREP •In addition to ADREP other data sources were used including: e.g. Airclaims, Aviation Safety Network, FSF, airline audits (LOSA), and incident report where available	•1990-2003	•World-wide	•World-wide accident / incident data is used, but the data are not assessed for their quality and potential for aggrega-tion	•Development of separate causal models for 7 accident types and 33 scenarios •Development of Event Sequence Diagrams (ESD) and Fault Trees for each accident type •Conversion of these single elements into a Bayesian Belief Net (BBN) •Validation: comparison with other models, expert peer review	•Causal factors •Failure probabilities for causal factors •Probability of an accident	•Modelling of accident causation scenarios •Quantitative appraoch •Extensive list of causal factors is given for excursions •Tool to support the decision making process of aviation stakeholders	•CATS includes also a model of collisions on runways, which is limited to pilot and ATC factors –> it takes on a flight perspective rather than a wider ATM perspective •Causal factors and failure probabilities are linked to specific accident scenarios and event chains •Many failure probabilities are based on SME judgement due to a lack of data •Aggregation of data with potential differing qualities
Australian Transport Safety Bureau (2008b, 2009): Runway excursions part 1: A worldwide	•Runway overruns during landing •Runway	•Accident Investigation Board	•Data from World Aircraft Accident Summary (WAAS)	•1998 - 2007	•World-wide	•World-wide accident data is used, but	•High-level data coding based on the UK CAA Accident Analysis Group	•List of causal factors •Most frequent causal factors •Outline of	•Extensive explanations of the causal factors and their implications, as well as risk controls	•Limited scope (i.e. only runway-related landing accidents) •Aggregation of data with potential differing

[25] National Aeronautics and Space Administration

review of commercial jet aircraft runway excursions; Runway excursions part 2: Minimising the likelihood and consequences of runway excursions	veer-offs during landing		•Complementary accident investigation reports from ATSB, NTSB, TSB, NTSC[26] and other national safety investigation bodies •Occurrences involving commercial jet aircraft			the data are not assessed for their quality and potential for aggrega-tion	(AAG) taxonomy; lower-level data coding using a classification scheme outlined in the FSF Approach-and-Landing Accident Reduction (ALAR) Toolkit Briefing Notes •Trend analysis •Frequency analysis of causal factors	preventive risk controls (i.e. recommendations for different aviation stakeholders) and recovery risk controls (i.e. available technologies and recommendations for airport design)		qualities •No discussion on the appropriateness of existing taxonomies •Only high-level statistical descriptive analysis
Es, 2005; Es, *et al.* (2009): 1) Running out of runway; 2) Development of a landing overrun risk index	•Runway overruns during landing	•National Aerospace Laboratory of the Netherlands (NLR) – Research institute	1) •NLR Air Safety Database •Commercial transport aircraft 2) •14,000 landings for narrow bodied aircraft (2004-2005)	•1970-2004	•World-wide	•World-wide accident data is used, but the data are not assessed for their quality and potential for aggrega-tion	1)•Development of a taxonomy of factors that influence landing performance •Analysis of safety data using this taxonomy •Trend analysis for landing overruns •Frequency analysis and calculation of risk ratios for each of the identified factors 2)Calculation of risk ratios for individual operators (airline)	•Estimation of risk associated with various landing factors and identification of factors that increase the landing overrun risk	•Proactive study that aims to identify hazards associated to landings	•Limited scope (i.e. only runway landing overrun accidents) •Unclear how the taxonomic factors were derived (e.g. literature, SMEs?) •Study stops with statistical associations, no causal relationship are analysed

[26] ATSB – Australian Transport Safety Bureau
NTSB – National Transportation Safety Board
TSB – Transportation Safety Board of Canada
NTSC – National Transportation Safety Committee of Indonesia

Federal Aviation Administration (2007a): Advisory circular 91-79 runway overrun prevention	•Runway overruns during landing	•Regulator / ANSP	•Not data based	•N/A	•N/A	•N/A	•N/A	•List of causal factors •Recommenda-tions for mitigation	•Raises awareness in the industry	•Limited scope (i.e. only runway overruns) •Very limited list of causal factors and associated recommendations is presented (i.e. four types of causal factors) •Not data based
Flight Safety Foundation (2009): Reducing the risk of runway excursions	•Runway veer-offs •Runway overruns	•International aviation safety consortium with members of more than 1,200 organisations in 150 countries (including e.g. aircraft manufacturers, airlines, airport operators, regulators)	•WAAS •Accidents involving Western- and Eastern-built commercial jet and turboprop	•1995 - 2008	•World-wide	•World-wide accident data is used, but the data are not assessed for their quality and potential for aggrega-tion	•Method for the extraction of the causal factors from the data is not specified •Frequency analysis of causal factors	•List of causal factors •Most frequent causal factors •Factor interactions •High-level recommendations for pilots, airport operators, ATM, regulators, and aircraft manufacturers	•The study represents the first major effort of the industry to address runway excursions	•Limited scope (i.e. only runway-related accidents) •Aggregation of data with potential differing qualities •Unknown methodology for the extraction of the causal factors •Only high-level statistical descriptive analysis
Flight Safety Foundation (2000): Approach-and-landing accident reduction (ALAR) briefing note 8.1 - Runway excursions and runway overruns; Methodology specified in: Khatwa and Helmreich (1999): Analysis of critical factors during approach and landing in accidents and normal flight	•Approach and landing accidents (ALA)	•International aviation safety consortium (as outlined above)	1) 287 fatal ALA accidents of jet and turboprop aircraft (maximum take-off weight above 12,500 pounds) from WAAS 2) 76 case studies of accidents and serious incidents using final occurrence reports from a variety of sources 3) Line audits of 3,000 flights	•1980-1997	•World-wide	•World-wide accident data is used, but the data are not assessed for their quality and potential for aggrega-tion	•1) Extraction of causal factors by analysing the descriptive narrative of occurrence reports 2) Data coding using a combination of taxonomies including AAG 3) Analysis of line audits •Trend analysis •Frequency analysis of causal factors	•1) Summary of causal factors in a taxonomy (UK CAA Accident Analysis Group (AAG) taxonomy) 2/3) List of causal factors and most frequent causal factors •Recommenda-tions for regulators, flight crews, ATC, airports, accident investigation boards, aircraft manufacturers, and the industry	•Use of a combination of safety data and operational audits •Good methodological approach •In-depth analysis of the causal factors that underlie ALA •Recommendations given for all aviation stakeholders	•Focus on ALA, not excursions in general •Limited list of causal factors for excursions •Aggregation of data with potential differing qualities •Only high-level statistical descriptive analysis

Hall, *et al*. (2008): Airport Cooperative Research Program (ACRP) Report 3. Analysis of aircraft overruns and undershoots for runway safety areas (Also published in: Ayres, *et al*. (2013): Modelling the location and consequences of aircraft accidents; Further results published in: Wong, *et al.* (2009a, b): The development of a more risk-sensitive and flexible airport safety area strategy: Part I. The development of an improved accident frequency model; Part II. Accident location analysis and airport risk assessment case studies)	•Runway landing overruns •Runway landing undershoots •Runway take-off overruns •Accidents and incidents	•Applied research program (including aviation consultants and academia)	•Data sources included mainly Accident Investigation Boards: FAA AIDS, FAA/NASA ASRS, NTSB, TSB, ICAO ADREP, ATSB, BEA, AAIB, TAIC, AAIB of Singapore, AAIU, CIAIAC[27] •Additional data sources were used to gather aircraft, airport, weather data	•1982-2006	•World-wide	•Problems associated to the quality of individual reports are discussed (e.g. missing info) •Data quality issues arising from the aggrega-tion of multi-national data sets are not addressed	•Functional Hazard Analysis to identify the relevant factors associated to runway overrun / undershoots events •Development of a database for runway overruns and undershoots •Frequency analysis of causal factors from occurrence reports •Development of risk models for event probability, location probability, and accident consequences •Software development	•List of causal factors •Most frequent causal factors •Runway safety area risk assessment (risk models)	•Quantitative risk assessment •Integration of frequency and location models for the evaluation of the likelihood of an accident with an accident consequences model	•Limited scope (i.e. no veer-offs) •Aggregation of data with potential differing qualities
International Air Transport Association (2011): Runway excursion analysis report 2004-2009	•Runway veer-off •Runway overrun	•Airline trade group	•IATA runway excursion data •Western and eastern built jet aircraft greater than 15,000 kg	•2004-2009	•World-wide	•World-wide accident data is used, but the data are	•Trend analysis •Frequency analysis of causal factors	•List of causal factors •Most frequent causal factors	•Good introduction to the main causal factors that underlie runway excursions	•Limited scope (i.e. only runway-related accidents) •Aggregation of data with potential differing qualities

[27] FAA AIDS – Federal Aviation Administration Accident / Incident Data System
FAA/NASA ASRS – FAA / National Aeronautics and Space Administration Aviation Safety Reporting System
NTSB – National Transportation Safety Board Accident Database & Synopses
TSB – Transportation Safety Board of Canada
ICAO ADREP – ICAO Accident / Incident Data Reporting system
ATSB – Australian Transport Safety Bureau
BEA - France Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile
AAIB – UK Air Accidents Investigation Branch
TAIC - New Zealand Transport Accident Investigation Commission
AAIB of Singapore - Air Accident Investigation Bureau of Singapore
AAIU - Ireland Air Accident Investigation Unit
CIAIAC - Spain Comisión de Investigación de Accidentes e Inci- dentes de Aviación Civil

			and turboprop aircraft greater than 5,700 kg			not assessed for their quality and potential for aggrega-tion				•Unknown methodology for the extraction of the causal factors •Only high-level statistical descriptive analysis
International Civil Aviation Organization / International Air Transport Association (2011): Runway Excursion Risk Reduction (RERR) toolkit	•Runway veer-off •Runway overrun	•Regulator / Airline trade group with contribution of others (e.g. safety organisations, national regulators, research institutes)	•The toolkit is based on the findings from the International Air Transport Association (2011) and other contributory reports from e.g. Australian transport safety Bureau *2008b, 2009); Flight Safety Foundation (2009); The European Organisation for the Safety of Air Navigation (2010d) are used as input for the toolkit	•N/A	•N/A	•N/A	•Knowledge compilation from various safety organisations and aviation industry stakeholders	•Toolkit that contains best practices, recommendations, and self audit checklists for airports, ANSPs, airlines, and regulators, as well as materials to support runway excursion workshops	•Industry awareness toolkit •Materials and recommendations for all relevant aviation stakeholders are provided	•Limited scope (i.e. only runway-related events) •Focus on prevention rather than analysis of causes •Based upon the findings of other reports and therefore their limitations apply
Ju (201): Fuzzy ANP-based research on the risk assessment on runway excursions	•No definition given	•Academia	•Not specified	•Not specified	•Not specified	•Not specified	•Definition of excursion risk factors •Fuzzy-Analytical Network Process (ANP) to model the key risk factors	•List of key risk factors for excursions	•Quantitative approach	•Missing definitions •It is unclear how the risk factors have been derived •It is not specified how the ANP has been modelled •Overall, the data sources and methodology remain unclear
The European Organisation for the Safety of Air Navigation, *et al.* (2013): European action plan	•Runway veer-off •Runway overrun	•Industry safety consortium	•Not data based	•N/A	•N/A	•N/A	•N/A	•Safety recommendations and guidance materials based on the results of the European	•Recommendations and guidance materials are given for all relevant stakeholders (i.e. airports, ANSPs,	•Recommendations are based on the results of the European Organisation for the Safety of Air Navigation (2010d)

for the prevention of runway excursions								Organisation for the Safety of Air Navigation (2010d) study and a consensus of SME expertise / knowledge	aircraft operator, aircraft manufacturer, regulator, EASA)	study that identified only 18 causal factors and does not address the impact of e.g. airports, ATC, regulators •Further limitations as outlined above apply
The European Organisation for the Safety of Air Navigation (2010d): A study of runway excursions from a European perspective	•Runway veer-off •Runway overrun	•Safety organisation	•NLR Air Safety Database •Jet and turboprop commercial and business transport flights	•1980-2008	•World-wide	•World-wide accident data is used, but the data are not assessed for their quality and potential for aggrega-tion	•Data coding using ECCAIRS / ADREP taxonomy •Trend analysis •Frequency analysis of causal factors •Calculation of risk ratios for each causal factor •Validation through SMEs	•List of most important causal factors •Risk ratio for each causal factor •Recommendations for preventive measures	•Results serve as input for the European Organisation for the safety of Air Navigation, *et al.* (2013) action plan •Comparison of excursion trends between Europe and the rest of the world	•Limited scope (i.e. only runway-related accidents) •Aggregation of data with potential differing qualities •Only high-level statistical descriptive analysis
The European Organisation for the Safety of Air Navigation SKYbrary (2012b): Runway excursion	•Runway overrun •Runway undershoot •Runway veer-off •Wrong runway use	•Industry safety consortium	•Not data based	•N/A	•N/A	•N/A	•N/A	•Introduction to typical runway excursion scenarios, including causes	•Raises awareness in the industry	•Limited scope (i.e. only runway-related events) •Very limited list of causal factors •Not data based •Overall, only a high-level introduction to runway excursions
Valdes, *et al.* (2011): The development of probabilistic models to estimate accident risk (due to runway overrun and landing undershoot) applicable to the design and construction of runway safety areas	•Runway overrun •Runway undershoot	•Academia / industry	•Data sources included mainly Accident Investigation Boards: AAIU, ATSB, BFU, TSB, BEA, CIAIAC, AAIB, AIDS, NMACS, NTSB[28]	•1984-2007	•World-wide	•World-wide accident data is used, but the data are not assessed for their quality and	•Analysis of accidents for their causal factors •Probability model for having an overrun or undershoot •Case study at one airport	•List of causal factors •Most frequent causal factors •Probability of having an overrun or undershoot	•Quantitative risk assessment	•Limited scope (i.e. only runway overruns and undershoots) •Aggregation of data with potential differing qualities •Unknown methodology for the extraction of causal factors from the safety

[28] AAIU - Ireland Air Accident Investigation Unit
ATSB – Australian Transport Safety Bureau
BFU – Bundesstelle fuer Flugunfalluntersuchung
TSB – Transportation Safety Board of Canada

			•Additional data sources from private entities were used			potential for aggrega-tion				data •The impact of the causal factors is not modelled
Ziegler (2012): Runway excursion modelling and analysis: a web-based geographic information system solution	•Runway overrun •Runway undershoot •Runway veer-off	•Academia	•NTSB data •Airport terrain data	•Past 20 years (study published in 2012)	•U.S.	•Data quality is not discussed	•Design of a geographic information system (GIS) that overlaps airport terrain data with the locations of previous runway excursions at similar airports	•GIS map that highlights specific danger zones of runways and past excursion points •The tool visualises the probability of an excursion occurring at specific locations along an airport's runway and its expected severity	•The tool allows making more informed decisions and to channel safety mitigation measures more effectively •The tool helps assessing whether proper mitigation measures are implemented at the correct areas of a runway	•Limited scope (i.e. only occurrences on runways) •Focus on the prediction of the location of runway veer-offs and overshoots, and their severity •Causal factors for excursions are not analysed •Purely graphical tool, not supported by statistical analysis

BEA - France Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile
CIAIAC - Spain Comisión de Investigación de Accidentes e Inci- dentes de Aviación Civil
AAIB – UK Air Accidents Investigation Branch
FAA AIDS – Federal Aviation Administration Accident / Incident Data System
NMACS – FAA Near Midair Collision System
NTSB – National Transportation Safety Board Accident Database & Synopses

Table 3: Literature overview on FOD

Reference	Scope	Represented stakeholder viewpoint	Data				Analytical methodology	Outcomes and proposed mitigation measures	Advantages	Disadvantages
			Data source	Time period	Region	Comments on data quality				
Bachtel (2010): Foreign Object Debris and Damage prevention	•FOD	•Aircraft manufacturer	•Not data based	•N/A	•N/A	•N/A	•No analysis	Specifies: •FOD sources •Elements of a FOD control program	•Outline of the elements of a FOD control program	•Compilation of knowledge •Not data-based
Federal Aviation Administration (1996, 2009a, 2010b): Advisory circular 150/5220-24; 150/5380-5B; 150/5210-24 on FOD	•FOD	•Regulator / ANSP	•Not data based	•N/A	•N/A	•N/A	•No analysis	Specifies: •FOD sources •FOD detection systems (technologies) •Requirements for a FOD management program	•Overview on available FOD detection technologies •Outline of the elements of a FOD control program	•Not data-based
Kraus and Watson (2001): Guidelines for the prevention and elimination of Foreign Object Damage / Debris (FOD) in the aviation maintenance environment through improved human performance	•FOD	•Industry (technology company) / regulator	•Not data based	•N/A	•N/A	•N/A	•No analysis	•Outlines two concepts of FOD prevention and their elements	•Emphasis on the human factors involved in FOD prevention	•Not data-based
(MBJ Airports (Year not specified): FOD awareness	•FOD	•Airport operator	•Not data based	•N/A	•N/A	•N/A	•No analysis	Specifies: •FOD sources •Elements of a FOD prevention program	•Outline of the elements of a FOD prevention program	•Compilation of knowledge •Not data-based
National Aerospace FOD Prevention Inc. (Year not specified): FOD prevention guideline	•FOD to aircraft	•Aerospace industry consortia	•Not data based	•N/A	•N/A	•N/A	•No analysis	Specifies: •FOD sources •Elements of a FOD control program •Best practices	•Report identifies that FOD that can damage aircraft	•Compilation of knowledge •Not data-based

Prather (2011): ACRP synthesis 26. Current airport inspection practices regarding FOD (Foreign Object Debris/Damage)	•FOD	•Consultant	•Stakeholder survey	•N/A	•U.S.	•N/A	•Literature review •Survey with airports •Survey with manufacturers / technology suppliers •Results are complemented by SME opinions	Specifies: •FOD sources •Types of FOD •Damage caused by FOD •Elements of FOD management programs •Overview on current FOD practices and available equipment and technologies that support a FOD control program	•Extensive review and synthesis of FOD knowledge •State-of-the-art overview on current FOD management practices	•Limited to FOD practices in the U.S. •Synthesis of knowledge, no analysis of safety knowledge •Results from the survey are only used qualitatively (frequency analysis of responses)
The European Organisation for the Safety of Air Navigation SKYbrary (2013b, c): Foreign Object Debris; Preventing FOD	•FOD	•Industry safety consortium	•Not data based	•N/A	•N/A	•N/A	•No analysis	Specifies: •FOD sources •Elements of a FOD control program	•Outline of the elements of a FOD control program	•Compilation of knowledge •Not data-based
The FOD Control Corporation (2010): FOD defined	•FOD	•Technology company for FOD prevention	•Not data based	•N/A	•N/A	•N/A	•No analysis	•High-level introduction to FOD and its sources		•Compilation of knowledge •Not data-based

Table 4: Literature overview on wildlife strikes

Reference	Scope	Represented stakeholder viewpoint	Data				Analytical methodology	Outcomes and proposed mitigation measures	Advantages	Disadvantages
			Data source	Time period	Region	Comments on data quality				
Airbus (2004a): Flight operations briefing notes. Birdstrike threat awareness	•Birds	•Aircraft manufacturer	•Not specified	•Not specified	•Not specified	•Not specified	•Analysis of Airbus bird strike occurrences (not further specified)	•Overview on operational consequences of bird strikes •Guidelines for bird strike prevention	•Good overview on the operational problems caused by bird strikes that airlines face	•Limited scope (i.e. only birds) •Unknown underlying data and methodology •Causal factors are not specified
Allan (2006): A heuristic risk assessment technique for birdstrike management at airports	•Birds	•Research institute	•UK CAA[29] Birdstrike Database	•1976-1996	•United Kingdom	•Data quality is not discussed	•Estimation of bird strike risk (severity estimation using linear regression, frequency estimation using a rolling mean) •Determination of risk category per species	•Methodology for the development of a bird strike risk assessment tool	•Proposed methodology can be adapted easily by any airport •Tool supports the identification and selection of management options	•Limited scope (i.e. only birds) •Only considers real strikes, not the presence of birds in general
Australian Airports Association (2005): Bird and animal hazard management plan	•Wildlife	•Airports association	•Not data based	•N/A	•N/A	•N/A	•N/A	•Introduction to the elements of a wildlife management plan	•Guidelines for wildlife management	•Not data-based •Causal factors are not specified •Focus on the mitigation of wildlife hazards
Australian Transport Safety Bureau (2008a): An analysis of Australian birdstrike occurrences 2002 to 2006	•Birds	•Accident investigation Board	•ATSB Aviation Safety Database •CSIRO bird species data •BITRE aircraft movement data[30] •Airservices	•2002-2006	•Austra-lia	•Data quality is not discussed	•Trend analysis •Identification of circumstantial factors	•Description of temporal and operational factors that were present during bird strikes and bird strike consequences	•Analysis of circumstances under which bird strikes most commonly occur	•Limited scope (i.e. only birds) •High-level statistical descriptive analysis

[29] UK CAA – United Kingdom Civil Aviation Authority
[30] ATSB – Australian Transport Safety Bureau
CSIRO – Commonwealth Scientific and Industrial Research Organisation
BITRE – Bureau of Infrastructure, Transport and Regional Economics

			Australia							
Dao-De, *et al.* (2010): Ranking birdstrike risk: A case study at Huanghua International Airport, Changsha, China	•Birds	•Airport / academia	•Survey (bird counts and observations)	•2006-2008	•Huang-hua Interna-tional Airport, China	•Data quality is not discussed	•Observation of bird over a 2-year period •Assessment of each species for 11 criteria •Calculation of a bird strike risk level for each species •Cluster analysis to cluster species into risk groups	•Four clusters of birds species (high-risk to low-risk species) in order to prioritise prevention measures	•Airport case study	•Limited scope (i.e. only birds) •The study analyses which birds are present at the airport and impose the greatest risk, without analysing as to why they are appear Appropriateness of the statistical model (i.e. multiplication of factors) is not discussed
Dennis and Lyle (2009): Bird strike damage & windshield bird strike. Final report	•Birds	•Research project under a European Aviation Safety Agency contract	•UK CAA •Transport Canada •USDA[31]	•1990-2007	•United States, Canada, United Kingdom	•Data quality is not discussed	•Trend analysis •Analysis of bird strikes for the damage they caused •Risk assessment based on strike frequency	•Overview on the consequences of bird strikes to aircraft •Conclusion that regulatory requirements are currently met	•Investigation of the adequacy of aircraft certification requirements	•Limited scope (i.e. only birds) •High-level statistical descriptive analysis •Causal factors are not specified •Risk is calculated based on occurrence rates only
Fennessy, *et al.* (2005): Ground versus air – seasonal changes in the use by birds of an Irish airport	•Birds	•Academia	•Survey (bird counts)	•1995-2002	•Dublin Airport, Ireland	•Data quality is not discussed	•Ground counts and counts of overflying birds •Comparison of bird counts to the airport's strike profile	•Species that are present at the airport •Seasonal distribution •Profile of strikes does not closely reflect the profile of species recorded during bird counts	•Comparison of bird strike and bird count profiles	•Limited scope (i.e. only birds) •Methodology is not specified in detail (e.g. how often bird counts were conducted) •Purely qualitative approach
Hesse, *et al.* (2010): Wildlife management practices at western Canadian airports	•Wildlife	•Academia	•Not data based	•N/A	•Canada	•N/A	•Survey with 38 airports	Overview on: •Causal factors •Animal control countermeasures and their effectiveness •Data collection systems	•Survey methodology, which can capture more details than safety data	•Limited scope (i.e. only birds) •High-level statistical descriptive analysis

[31] UK CAA – United Kingdom Civil Aviation Authority
USDA – U.S. Department of Agriculture

								•Bird strike trends that Canadian airports experience		
International Birdstrike Committee (2006): Standards for aerodrome bird / wildlife control; Adapted by Cleary (2007) Best management practices for airport wildlife control	•Birds / wildlife	•Industry consortia	•Not data based	•N/A	•N/A	•N/A	•Development of recommendations for wildlife management based on a global consensus / state of knowledge from ornithological and aviation experts	•Recommended practices for airfield habitat management, wildlife dispersal and removal, and data reporting and analysis	•Recommendations for wildlife management	•Causal factors are not specified •Based on SME expertise, not supported by data analysis
International Civil Aviation Organization (1991): Airport services manual part 3. Bird control and reduction	•Birds	•Regulator	•ICAO Bird Strike Information System (IBIS)	•Un-known	•World-wide	•World-wide bird strike data is used, but the data are not assessed for their quality	•Trend analysis •Development of recommendations for an airport bird strike control program	•Causal factors •Recommenda-tions for the development and implementation of a bird strike control program	•High-level guidelines for the development of a bird strike control program	•Limited scope (i.e. only birds) •It remains unclear whether ICAO has done the data analysis or whether the document refers to the results of another study •Unknown where the causal factors come from
Laty (1982): Birds on airports and the reason for their presence	•Birds	•Unknown	•Not data based	•N/A	•N/A	•N/A	•N/A	•Causal factors	•Early study that provides already a comprehensive overview on the types of causal factors	•Limited scope (i.e. only birds) •Unknown where the causal factors come from
Manktelow (2000): The effect of local weather conditions on bird-aircraft collisions at British airports	•Birds	•Research institute	•Bird strike data from MAFF[32] •Meteorological Office of England and Wales	•1976-1995	•Nine airports in the United Kingdom	•Data quality is not discussed	•Statistical analysis	•Investigation of the role of weather	•Detailed analysis of the role of weather conditions	•Limited scope (i.e. only birds)
Maragakis (2009): Bird population trends and their impact on aviation safety 1999-	•Birds	•European Aviation Safety Agency (regulator)	•Bird strike accident data from ICAO, UK CAA, and EURBASE[33]	•1999-2008	•World-wide	•Data quality is not discussed	•Trend analysis	•Bird population trends	•Bird population trends	•Limited scope (i.e. only birds) •High-level statistical descriptive analysis

[32] MAFF - Central Science Laboratory of the Ministry of Agriculture, Fisheries and FOOD
[33] ICAO –International Civil Aviation Authority
UK CAA – UK Civil Aviation Authority
EURBASE – European military bird strike database

2008										
Nikolaidis and Koloka (2005): Bird strike in Hellas – Civil Aviation	•Birds	•Consultants	•ICAO Bird Strike Information System (IBIS) •Airport data (not further specified)	•Until 2004	•Greece	•Data quality is not discussed	•Trend analysis	•List of causal factors •Outline of available dispersal methods and bird strike avoidance methods used in Greece	•National overview on the bird strike situation in Greece	•Limited scope (i.e. only birds) •High-level statistical descriptive analysis •Unknown where the causal factors come from
Soldatini, *et al.* (2010): An ecological approach to birdstrike risk analysis	•Birds	•Academia	•Survey (bird counts and observations) •Airport movement and bird strike data	•2006-2007	•Venice Airport, Italy	•Data quality is not discussed	•Observation of bird over a 2-year period •Statistical analysis	•Birdstrike Risk Index (BRI)	•Quantitative approach •BRI describes the risk on the basis of the actual presence of birds at airports	•Limited scope (i.e. only birds) •Appropriateness of the statistical model (i.e. multiplication of factors) is not discussed) •Consideration of only species that have had a strike before
Steele (2001): Factors influencing the incidence of bird-strikes at Melbourne Airport	•Birds	•Academia	•Survey (bird counts) •ATSB bird strike data •Airport movement data •BOM weather data[34]	•1997-2000	•Mel-bourne Airport, Australia	•Data quality is not discussed	•Trend analysis •Tests for statistical associations •Identification of circumstantial factors	•Description of temporal and operational factors that were present during bird strikes	•Airport case study •Analysis of circumstances under which bird strikes most commonly occur	•Limited scope (i.e. only birds)
The European Organisation for the Safety of Air Navigation SKYbrary (2013a): Bird strike	•Birds	•Industry safety consortium	•Not data based	•N/A	•N/A	•N/A	•N/A	•Introduction to typical bird strike scenarios, including causes	•Raises awareness in the industry	•Limited scope (i.e. only birds) •Not data based •Overall, only a high-level introduction to bird strikes
Transport Canada (2002, 2010a): Sharing the skies (TP13549); Wildlife control procedures manual (TP11500)	•Wildlife	•Regulator	•Not data based	•1991-1999	•Canada, United States	•Data quality is not discussed, but an under-reporting of the data acknowled-ged	•Trend analysis •Development of recommendations for wildlife management	•Bird population trends •Description of temporal and operational factors that were present during bird strikes •Recommenda-tions for the development and	•Detailed overview on the bird strike problem, bird control measures •Recommendations for all aviation stakeholders to mitigate bird strikes	•High-level statistical descriptive analysis

[34] ATSB – Australian Transport Safety Bureau
BOM – Bureau of Meteorology

								implementation of a bird strike control program		
UK Civil Aviation Authority (2008a): CAP 772 Birdstrike risk management for aerodromes	•Birds / wildlife	•Regulator	•Not data based	•N/A	•N/A	•N/A	•Development of guidelines for bird strike risk management for airports	•Causal factors •Recommended practices for bird strike risk identification, reduction, and reporting	•Recommendations for wildlife management	•Not data-based •Unknown where the causal factors come from

Appendix III: Semi-Structured Interview Questions

1. Who can make a report?
2. How does the underlying reporting form look like? May I have a copy?
3. How are occurrences reported (e.g. electronic reporting form, per telephone, post, email)?
4. Is some of the information captured automatically (i.e. automatic recordings)?
5. Is some of the information captured through multiple sources?
6. Is your database a primary database? If not, which of the original information goes into your database and what happens to the information that does not go into your database? How does the raw data look like?
7. If your database is a secondary database, how is the information transferred from the primary data collection system to the secondary database (e.g. manually / automatic)?
8. Does the database contain the original reports that people submitted or is it a summary report written by an investigator and / or analyst?
9. How is the information processed? What happens after a report is received?
10. Are you investigating every incident? If not, who is investigating and at what stage?
11. How are incidents followed-up (e.g. feedback to the reporters), and what happens with the data (e.g. use for safety mitigation measures)?
12. What kind of safety statistics / documents does your organisation produce?
13. Do you report to somebody else apart from regulatory requirements (i.e. do you share your data with other organisations)? If yes, to whom?
14. Within recent years, have there been any changes in the reporting system?
15. Do you see any limitations in the reporting system, e.g. where could information get lost, and where could errors arise?
16. If you could do anything to make the reporting system better, with no budget limits or time constraints, would you do anything? What would it be?
17. What are the underlying definitions for your data? Have there been any changes?

Appendix IV: Evaluation of MCDA Techniques

Chapter 6 developed a weighting scheme for safety databases based on MCDA. The choice of an appropriate MCDA method depends on the data input and assumption, the required output and methodological requirements. This appendix evaluates different MCDA methods for their applicability to the current decision problem. Elementary methods, single synthesising criteria methods, outranking and qualitative methods are evaluated.

1 Elementary Methods

Elementary methods reduce a complex problem to a singular basis and are suitable for single-decision makers with a few alternatives and criteria. Disadvantageous is that elementary methods do not necessarily weight the relative importance of criteria. In addition, they combine the criteria to produce an aggregate score.

Table 1: MCDA - Elementary methods

Class of methods	**Elementary**				
Method	**Weighted Sum Method (WSM)**	**Weighted Product Method (WPM)**	**Conjunctive Method**	**Disjunctive Method**	**Simple Dominance**
Output					
Solution (Rank / Choice / Classification / Description)	Rank & Choice	Rank & Choice	Classification & Choice	Classification & Choice	Choice (best solution)
Quantitative output	✓	✓	Quantitative, qualitative, mixed depending on input	Quantitative, qualitative, mixed depending on input	Quantitative, qualitative, mixed depending on input
Output for all options	✓	✓	✗	✗	✗
Input / Assumptions					
Data input (qualitative / quantitative / mixed)	Discrete, however, qualitative data can be incorporated	Discrete, however, qualitative data can be incorporated	Quantitative, qualitative, mixed possible	Quantitative, qualitative, mixed possible	Quantitative, qualitative, mixed possible
Finite amount of options	✓	✓	✓	✓	✓
Predefined set of alternatives	✓	✓	✓	✓	✓
Static preferences	✓	✓	✗ Threshold can change	✗ Threshold can change	✓
Independence of options and criteria	✓	✓	✓	✓	✓
Certainty	✓	✓	✓	✓	✓

Methodology					
Hierarchical model	✗	✗	✗	✗	✗
Comparison to a reference system possible	Can be incorporated during scoring	Can be incorporated during scoring	Reference system could be set as threshold	Reference system could be set as threshold	Can be incorporated during scoring
Method of weighting	Direct	Direct	Direct	Direct	Direct
Compensation of criteria	✓	✓	✗	✗	✗
Methodology takes all criteria into acc.	✓	✓	✓	✓	✓
Simplicity	✓	✓	✓	✓	✓
Description	• Criteria are defined and weighted • Alternatives are scored on the criteria • Scores and weights are aggregated using an additive relationship assuming that the sum of all weighted criteria impacts on the solution	• Criteria are defined and weighted • Alternatives are scored on the criteria • Scores and weights are aggregated using a multiplicity relationship	• Minimal acceptance levels for each criterion are used to screen out unacceptable alternatives • All alternatives are considered • Alternatives that do not meet the minimal acceptable level for all criteria are rejected	• Disjunctive method assumes no acceptable alternative at the beginning • Lower thresholds are specified for each criterion • Alternatives that meet the required criteria values are accepted	• Method aims to identify a 'non-dominated' solution • An alternative is dominant when it is better in at least one criterion without being worse in all other criteria • Pairwise comparison is used, the dominating solution is retained and compared to the next alternative until the best alternative is identified
Overall evaluation					
Applicability	Applicable	Applicable, however, multiplicity relationship seems inadequate	Not applicable	Not applicable	Not applicable
References	Garoufalia (2007); Guitouni and Martel (1998); Hwang and Yoon (1981); Wang, *et al.* (2009)	Triantaphyllou and Sanchez (1997)	Antunes and Dias (2012); Guitouni and Martel (1998); Hwang and Yoon (1981)	Antunes and Dias (2012); Guitouni and Martel (1998); Hwang and Yoon (1981)	Antunes and Dias (2012); Hwang and Yoon (1981)

Table 1: MCDA - Elementary methods - continued

Class of methods	**Elementary**				
Method	**Maximin**	**Maximax**	**Lexicographic**	**Linear assignment method**	
Output					
Solution (Rank / Choice / Classification / Description)	Choice (best solution)	Choice (best solution)	Choice (best solution)	Rank	
Quantitative output	Quantitative, qualitative depending on input	Quantitative, qualitative depending on input	Quantitative, qualitative depending on input	Quantitative, qualitative depending on input	
Output for all options	✗	✗	✓	✓	
Input / Assumption					
Data input (qualitative/ quantitative/ mixed)	Quantitative, qualitative possible (all criteria must use a common scale)	Quantitative, qualitative possible (all criteria must use a common scale)	Quantitative, qualitative, mixed possible	Quantitative, qualitative possible (all criteria must use a common scale)	
Finite amount of options	✓	✓	✓	✓	
Predefined set of alternatives	✓	✓	✓	✓	
Static preferences	✓	✓	✓	✓	
Independence of options and criteria	✓	✓	✓	✓	
Certainty	✓	✓	✓	✓	
Methodology					
Hierarchical model	✗	✗	✗	✗	
Comparison to a reference system possible	Can be incorporated during scoring	Can be incorporated during scoring	Can be incorporated during scoring	Can be incorporated during scoring	

Method of weighting	Direct	Direct	Direct	Direct	
Compensation of criteria	✗	✗	✗	✓	
Methodology takes all criteria into acc.	✗	✗	✓	✓	
Simplicity	✓	✓	✓	✓	
Description	• The performance of an option is determined on the basis of a single criterion • Method tries to maximise the poorest performing criteria • The weakest criterion for each alternative is identified • The alternative with the highest score on the weakest criterion is preferred	• The performance of an option is determined on the basis of a single criterion • The best performing criterion is identified for each alternative • The alternative with the highest score on the best criterion is preferred	• Criteria are weighted • The option with the highest score on the highest weighted criterion is preferred	• All alternatives are ranked for each of the criteria • Alternatives with many high ranked criteria are ranked highest	
Overall evaluation					
Applicability	Not applicable	Not applicable	Not applicable	Not applicable	
References	Antunes and Dias (2012); Guitouni and Martel (1998); Hwang and Yoon (1981)	Antunes and Dias (2012); Hwang and Yoon (1981)	Antunes and Dias (2012); Guitouni and Martel (1998); Hwang and Yoon (1981)	Hwang and Yoon (1981)	

2 Single synthesising criteria methods

Single synthesising criteria approaches seek to build a unique criterion taking into account all the relevant aspects of the decision problem.

Table 2: Single synthesising criteria methods

Class of methods	**Single synthesising criteria**				
Method	**Analytical Hierarchy Process (AHP)**	**Multi Attribute Utility Theory (MAUT)**	**Multi Attribute Value Theory (MAVT)**	**Simple Multi Attribute Rating Technique (SMART)**	**Utilities Additives (UTA)**
Output					
Solution (Rank / Choice / Classification / Description)	Rank & Choice	Rank & Choice	Rank & Choice	Rank & Choice	Underlying preference model for ranked data
Quantitative output	✓	✓	✓	✓	✓
Output for all options	✓	✓	✓	✓	✗ Quant. value function
Input / Assumptions					
Data input (qualitative / quantitative / mixed)	Mixed data possible	Mixed data possible	Mixed data possible	Mixed data possible	Quantitative ranking of options
Finite amount of options	✓	✓	✓	✓	✓
Predefined set of alternatives	✓	✓	✓	✓	✓
Static preferences	✓	✓	✓	✓	n/a
Independence of options and criteria	✓	✓	✓	✓	✓
Certainty	✓	✓	SME-approach	SME-approach	✓
Methodology					

Hierarchical model	✓	✓	✗	✓	
Comparison to a reference system possible	✗	Can be incorporated during scoring	✗	✗	✗
Method of weighting	Pairwise comparison	Different weighting methods possible	Different weighting methods possible	Different weighting methods possible	n/a
Compensation of criteria	✓	✓	✓	✓	✓
Methodology takes all criteria into acc.	✓	✓	✓	✓	n/a
Simplicity	✓	✓	Fair Stakeholder input to a large extent required	Fair Good judgment needed	No
Description	• Decision problem is modeled hierarchically • Criteria are weighted and alternatives are scored through pairwise comparison • Global priorities are calculated	• User preferences are defined in relation to the criteria • User preferences and weighted scores are aggregated • MAUT selects the alternative that fulfills best user requirements	• Similar to WSM, however MAVT uses SME preferences to score the alternatives on the options rather than actual performance	• Similar to WSM, however SMART uses value functions rather than actual performance • During scoring the analyst assesses the value of an alternative on a criterion	• UTA is a disaggregation-aggregation approach • The decision is known and the ranking of options is given, the aim is to determine the underlying preference model • Assumes an underlying additive value function
Overall evaluation					
Applicability	Applicable, however not appropriate as the alternatives cannot be compared to a reference system	Not appropriate as it evaluates alternatives according to user preferences	Not appropriate as MAVT is based on SME preferences	Not applicable, as a value function cannot be determined for the current problem	Not applicable, as it decomposes the final ranking
References	Guitouni and Martel (1998); Ramanathan and Ramanathan (2010); Wang, *et al.* (2009)	Dias and Antunes (2010); Schaefer (2001)	Dias and Antunes (2010); Hostmann, *et al*. (2005)	Kriwaczek (2011)	Siskos, *et al.* (2005)

Table 2: Single synthesising criteria methods - continued

Class of methods	**Single synthesising criteria**
Method	**Technique for Order Preference by Similarity (TOPSIS)**
Output	
Solution (Rank / Choice / Classification / Description)	Rank & Choice
Quantitative output	✓
Output for all options	✓
Input / Assumptions	
Data input (qualitative / quantitative / mixed)	Quantitative, qualitative possible
Finite amount of options	✓
Predefined set of alternatives	✓
Static preferences	✓
Independence of options and criteria	✓
Certainty	✓
Methodology	
Hierarchical model	✗
Comparison to a reference system possible	✓

Method of weighting	Direct weighting
Compensation of criteria	✓
Methodology takes all criteria into acc.	✓
Simplicity	Fair
Description	• TOPSIS aims to find the solution that is nearest to an ideal solution and furthest from a negative-ideal solution
Overall evaluation	
Applicability	Applicable
References	Jaditi, *et al.* (2010)

Single synthesising criteria methods using fuzzy methods exist. Fuzzy logic can process incomplete data and finds an approximate solution. It deals with reasoning that is approximate rather than fixed/exact. As the current decision problem assumes certainty fuzzy methods are not considered (Figueira, *et al.,* 2005).

3 Outranking

Outranking methods are appropriate for complex choice problems with multiple criteria and multiple participants. Outranking indicates the degree of dominance of one alternative over another. Outranking methods are based on pairwise comparison and provide a preference ranking of alternatives, not a cardinal measure of preference relations. Outranking methods do not assume a certain functional form and can perform with incomplete value information. The aim of the current study is to measure how good each of the reporting systems performs in relation to an ideal system, rather than comparing the reporting systems against each other. Thus, outranking methods are excluded from this assessment, as they do not suit the underling problem (Figueira, *et al.,* 2005).

4 Qualitative methods

This section evaluates qualitative MCDA methods.

Table 3: MCDA – Qualitative methods

Class of methods	**Qualitative Methods**				
Method	**QUALItative and FLEX ible assessment (Qualiflex)**	**Regime**	**Organisation, rangement et synthese de donnees relationnelles (ORESTE)**	**Achieving Respect for Grades by Using ordinal Scales (ARGUS)**	**Evaluation matrix (EVAMIX)**
Output					
Solution (Rank / Choice / Classification / Description)	Ranking & Choice	Ranking & Choice	Ranking & Choice	Rank	Ranking & Choice
Quantitative output	Index	Index	Index	✗	Index
Output for all options	For all combinations of alternatives	✓	✓	✓	✓
Input / Assumptions					
Data input (qualitative/ quantitative/ mixed)	Qualitative (binary)	Qualitative (binary)	Qualitative (binary)	Qualitative (ordinal)	Mixed data is required

Finite amount of options	✓	✓	✓	✓	✓
Predefined set of alternatives	✓	✓	✓	✓	✓
Static preferences	✓	✓	✓	✓	✓
Independence of options and criteria	✓	✓	✓	✓	✓
Certainty	✓	✓	✓	✓	✓
Methodology					
Hierarchical model	✗	✗	✗	✗	✗
Comparison to a reference system possible	✗	✗	✗	✗	✗
Method of weighting	Different weighting methods possible	Different weighting methods possible	Different weighting methods possible	Different weighting methods possible	Different weighting methods possible
Compensation of criteria	✓	✓	✓	✓	✓
Methodology takes all criteria into acc.	✓	✓	✓	✓	✓
Simplicity	No (Computational requirements)	No (Computational requirements)	No (Computational requirements)	Fair	No (Computational requirements)
Description	• QUALIFLEX evaluates all possible rankings (permutations) of alternatives • Alternatives are pre-ordered • Using pairwise comparison QUALIFLEX computes a concordance index for each pair of alternatives • QUALIFLEX aims to maximise the value of these indices	• REGIME is an ordinal generalisation of pairwise comparisons for binary data	• Applicable to problems where the alternatives are ranked according to each criterion and the criteria are ranked according to their importance	• Based on pairwise comparison • ARGUS uses ordinal values to express the intensity of preference between two alternatives	• Based on pairwise comparison • Separate concordance indices are constructed for qualitative and quantitative criteria • Overall dominance measure for an alternative is determined as the sum of the weighted indices
Overall evaluation					
Applicability	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
References	Figueira, *et al.* (2005)	Figueira, *et al.* (2005)	Figueira, *et al.* (2005)	Figueira, *et al.* (2005)	Figueira, *et al.* (2005)

Table 3: MCDA – Qualitative methods - continued

Class of methods	**Qualitative Methods**	
Method	**DEX**	**Measuring attractiveness by a categorical based evaluation technique (MACBETH)**
Output		
Solution (Rank / Choice / Classification / Description)	Description	Rank & Choice
Quantitative output	✗	✓
Output for all options	✓	✓
Input / Assumptions		
Data input (qualitative / quantitative / mixed)	Qualitative	Designed for qualitative data, but mixed possible
Finite amount of options	✓	✓
Predefined set of alternatives	✓	✓
Static preferences	✓	✓
Independence of options and criteria	✓	✓
Certainty	✓	✓
Methodology		
Hierarchical model	✓	✓
Comparison to a reference	Can be incorporated during	✗

system possible	scoring	
Method of weighting	Different weighting methods possible	Direct weighting
Compensation of criteria	✓	✓
Methodology takes all criteria into acc.	✓	✓
Simplicity	✓	✓
Description	• DEX provides a visual representation of the scoring of alternatives on the criteria	• MACBETH measures attractiveness between alternatives (i.e. which alternative is more attractive and what is the distance between the options) • Based on pairwise comparison
Overall evaluation		
Applicability	Not appropriate, as only graphical output	Not appropriate, as the alternatives cannot be compared to a reference system
References	Rozman, *et al.* (2009)	Joerin, *et al.* (2010)

Appendix V: Analysis of Causal Factors - Supplementary Analysis

Table 1: Top five airports with the highest occurrence rates per region U.S.

Airport[1]	Region	Normalised number of incursions	Total movements 2005-2009
1	U.S. Northeast	8.64	196,771
2	U.S. Northeast	7.10	436,339
3	U.S. Northeast	4.29	933,455
4	U.S. Northeast	3.69	1,976,749
5	U.S. Northeast	3.46	491,337
1	U.S. Mountain Region	49.31	2,028
2	U.S. Mountain Region	8.71	218,107
3	U.S. Mountain Region	7.44	215,142
4	U.S. Mountain Region	5.81	154,983
5	U.S. Mountain Region	4.77	419,716
1	U.S. Southwest	6.47	648,994
2	U.S. Southwest	5.67	511,838
3	U.S. Southwest	4.60	239,288
4	U.S. Southwest	4.15	433,507
5	U.S. Southwest	3.85	285,825
1	U.S. Western-Pacific	7.64	982,250
2	U.S. Western-Pacific	7.59	65,910
3	U.S. Western-Pacific	6.89	420,670
4	U.S. Western-Pacific	5.22	230,008
5	U.S. Western-Pacific	4.79	772,259

[1] For sensitivity reasons the airports are de-identified.

Table 2: Descriptives operations U.S. Northeast, Mountain Region, Southwest, Western-Pacific

Region	Mean	Std. Deviation	Minimum	Maximum
U.S. Northeast	624,595.96	535,334.95	122,591	2,516,410
U.S. Mountain Region	582,939.26	582,979.37	2,028	3,034,827
U.S. Southwest	577,444.66	579,850.49	136,708	3,401,728
U.S. Western-Pacific	836,899.109	601,792.65	135,380	3,155,674

Table 3: Causal factors (Level 3) U.S. per stakeholder

Causal factor	Responsibility	Database		
		RI Database	AIDS	SHEBBA
1 Aircraft operations				
1 Aircraft - Technical	Airline, Engineers, Aircraft manufacturer, Ground-handling			
111 Aircraft technical failure		0.65%	28%	
112 Aircraft weight and balance			0.36%	
113 Master caution warning				
114 Aircraft design/manufacturing				
115 Aircraft improper maintenance			0.55%	
116 Environmental influences			0.18%	
12 Pilot - Human	Pilot			
121 Resources			0.18%	
122 Competence		1.24%	5.09%	
123 Communication		15.17%		
124 Situational awareness		4.20%		
125 Human-machine interface		0.11%		
126 Human reliability		45.89%	41.27%	
127 Team operations		0.04%	0.55%	
128 Procedures		1.39%		
2 ATC				
21 ATC - Technical	ANSP, Engineers, Equipment manufacturer	0.06%		
211 Surveillance system				
212 Navigation system				
213 Communication system				
214 Equipment design/manufacturing				
215 Equipment improper maintenance				
22 ATC - Human	ATC			
221 Resources		0.06%		
222 Competence		0.02%		
226 Communication		1.85%		
223 Situational awareness		1.78%		
224 Human-machine interface		0.02%		
225 Human reliability		3.74%	0.18%	
227 Team operations		1.22%		
228 Procedures		0.08%		
3 Airport operations				
31 Airport – Technical	Airport authority, Ground-handling, Engineers, Equipment manufacturer	0.04%		
311 Vehicle technical failure				
312 Radio communication				
313 Absence of radar beacon				
314 Ground handling equipment				3.78
315 Tugs				
316 Airport meteorological equipment				
317 Vehicle/equipment design/manufacturing				
318 Vehicle/equipment improper maintenance				
319 Other		0.04%		
32 V/PD - Human	V/PD, Airport authority			
321 Resources		0.02%		7.55%
322 Competence		0.04%		1.89%
326 Communication		1.62		
323 Situational awareness		0.06%		
324 Human-machine interface				
325 Human reliability		20.14%		64.12%

327 Team operations		0.06%		1.89%
328 Airport management		0.04%		
329 Airport operations		0.04%		
330 Procedures		0.02%		1.89%
33 Airport - Physical	Airport authority, Airport planner			
331 Airport design		0.13%	0.18%	1.89%
332 Surface infrastructure and conditions		0.09%	10.73%	13.21%
4 Environment				
41 Weather	External influences			
411 Winds			11.64%	
412 Turbulence/Wake vortex		0.02%		
413 Insufficient visual reference/low visibility conditions		0.11%		
414 Snow/Ice			1.09%	
415 Rain/aquaplaning				1.89%
416 Nice weather				
417 Other				
42 Geological disturbances				
43 Night time operations				
44 Wildlife				
45 External factors				1.89
5 Regulatory system	Regulator			

Legend:

> 20.0% of causal factors fall into this category
Between 10.0 and 20.0% of causal factors fall into this category
Between 5.0 and 10.0% of causal factors fall into this category
< 5.0% of causal factors fall into this category

Table 4: Top five airports with the highest occurrence rates per organisation UK

Stakeholder / airport[1]	Region	Normalised number of occurrences**	Total movements 2005-2009
UK CAA*			
1	UK	48.72	22,579
2	UK	36.41	10,985
3	UK	30.07	23,277
4	UK	21.67	18,808
5	UK	20.09	139,379
easyJet			
1	Europe	203.80	1,472
2	Europe	59.45	3,364
3	Africa	86.28	1,159
4	Africa	63.85	1,566
5	Europe	59.74	1,674

[1] For sensitivity reasons the airports are de-identified.
*Considers only the 50 airports for which movement data was available
** Excluding wildlife

Table 5: Descriptives operations UK

Organisation	Mean	Std. Deviation	Minimum	Maximum
UK CAA	114,651.42	149,363.41	4,016	921,216
easyJet	34,212.54	37,063.57	3	173,891

Table 6: Causal factors (Level 3) UK per stakeholder

Causal factor	Responsibility	Database		
		MORS	AQD	SHEBBA
1 Aircraft operations				
1 Aircraft - Technical	Airline, Engineers, Aircraft manufacturer, Ground-handling	5.99%		
111 Aircraft technical failure				
112 Aircraft weight and balance		0.21%		
113 Master caution warning				
114 Aircraft design/manufacturing		0.15%		
115 Aircraft improper maintenance		0.05%		
116 Environmental influences				
12 Pilot - Human	Pilot			
121 Resources		0.31%	1.33%	
122 Competence		2.53%	0.44%	
123 Communication		7.90%	4.87%	
124 Situational awareness		4.13%	13.72%	
125 Human-machine interface				
126 Human reliability		49.15%	29.20%	2.04%
127 Team operations		0.05%		
128 Procedures		0.52%		
2 ATC				
21 ATC - Technical	ANSP, Engineers, Equipment manufacturer			
211 Surveillance system				
212 Navigation system				
213 Communication system		0.05%	0.44%	
214 Equipment design/manufacturing				
215 Equipment improper maintenance				
22 ATC - Human	ATC			
221 Resources		0.26%		
222 Competence		0.15%		
226 Communication		1.34%	2.65%	
223 Situational awareness		1.60%		
224 Human-machine interface				
225 Human reliability		1.24%	3.10%	
227 Team operations		0.10%		
228 Procedures		0.21%		
3 Airport operations				
31 Airport - Technical	Airport authority, Ground-handling, Engineers, Equipment manufacturer			
311Vehicle technical failure				
312 Radio communication		0.36%	0.44%	
313 Absence of a radar beacon				
314 Ground handling equipment				1.02%
315 Tugs				
316 Airport meteorological equipment				
317 Vehicle/equipment design/manufacturing				
318 Vehicle/equipment improper maintenance				
319 Other				
32 V/PD - Human	V/PD, Airport authority			
321 Resources		0.05%		2.04%
322 Competence		0.26%		
326 Communication		0.77%		
323 Situational awareness		1.14%	0.44%	1.02%
324 Human-machine interface		0.15%		
325 Human reliability		9.09%	1.77%	54.08%

327 Team operations		0.21%		1.02%
328 Airport management		0.05%	0.44%	
329 Airport operations				
330 Procedures		0.41%		
33 Airport - Physical	Airport authority, Airport planner			
331 Airport design			2.21%	
332 Surface infrastructure and conditions		5.22%	33.67%	33.67%
4 Environment				
41 Weather	External influences			
411 Winds		3.41%		4.08%
412 Turbulence/Wake vortex		0.46%		
413 Insufficient visual reference/low visibility conditions		1.45%	0.88%	
414 Snow/Ice		0.72%		
415 Rain/aquaplaning		0.41%		
416 Nice weather				
416 Other				
42 Geological disturbances		0.05%		
43 Night time operations				
44 Wildlife			4.4%	
45 External factors				1.02
5 Regulatory system	Regulator	0.05%		

Legend:

> 20.0% of causal factors fall into this category
Between 10.0 and 20.0% of causal factors fall into this category
Between 5.0 and 10.0% of causal factors fall into this category
< 5.0 % of causal factors fall into this category

Table 7: Top five airports with the highest occurrence rates per organisation – Norway

Stakeholder / airport[1]	Region	Normalised number of occurrences*	Total movements 2005-2009
CAA-Norway			
1	Norway	138.67	10,817
2	Norway	129.84	24,646
3	Norway	90.81	6,607
4	Norway	94.07	10,630
5	Norway	60.89	26,277
Avinor-ANSP			
1	Norway	259.38	9,253
2	Norway	94.07	10,630
3	Norway	105.95	6,607
4	Norway	64.71	10,817
5	Norway	63.82	9,402
Avinor-Airports			
1	Norway	110.94	10,817
2	Norway	77.09	24,646
3	Norway	68.50	26,277
4	Norway	59.59	43,629
5	Norway	54.98	7,275
OSL			
1	Oslo	30.22	675,080

[1] For sensitivity reasons the airports are de-identified.

* Excluding wildlife

Table 8: Descriptives operations Norway

Stakeholder	Mean	Std. Deviation	Minimum	Maximum
CAA-Norway	52,176.04	108,882.14	3,546	675,080
Avinor-ANSP	100,017.10	153,297.19	6,607	675,080
Avinor-Aiports	39,246.10	61,546.79	3,546	284,078
OSL	675,080	675,080	675,080	675,080

Table 9: Causal factors (Level 3) Norway per stakeholder

Causal factor	Responsi-bility	Database					
		ECCAIRS	MESYS (ATC)	MESYS (Air-ports)	IFS	AQD	Sentinel
1 Aircraft operations							
1 Aircraft - Technical	Airline, Engineers, Aircraft manufac-turer, Ground-handling						
111 Technical failure		1.82%	0.80%	0.24%	1.38%	1.04%	
112 Aircraft weight and balance		0.13%		0.24%			
113 Master caution warning				0.24%		1.04%	
114 Aircraft design/manufacturing							
115 Aircraft improper maintenance					0.34%		
116 Environmental influences							
12 Pilot - Human	Pilot						
121 Resources		0.39%	0.16%			6.25%	7.69%
122 Competence		1.04%	0.80%				
123 Communication		2.73%	6.87%		37.42 %	4.17%	19.23 %
124 Situational awareness		2.73%	3.19%		1.03%	11.46 %	9.62%
125 Human-machine interface		0.39%	0.16%			6.25%	
126 Human reliability		23.87 %	38.65 %	8.21%	0.74%	45.82 %	46.15 %
127 Team operations						3.13%	
128 Procedures			0.16%				7.69%
2 ATC							
21 ATC - Technical	ANSP, Engineers, Equipment manufac-turer						
211 Surveillance system			0.16%				
212 Navigation system							
213 Communication system							
214 Equipment design/ manufacturing							
215 Equipment improper maintenance							
22 ATC - Human	ATC						
221 Resources		0.26%	0.32%				
222 Competence		0.39%	0.48%		0.34%		
226 Communication		1.43%	2.72%	1.74%	1.38%	4.17%	9.62%
223 Situational awareness		1.43%	3.35%	0.24%	2.76%		
224 Human-machine interface							
225 Human reliability		1.30%	1.76%	0.49%	2.07%	5.21%	
227 Team operations		0.26%	0.16%	0.49%	0.34%		
228 Procedures			0.16%	0.24%		1.04%	
3 Airport operations							
31 Airport– Technical	Airport authority, Ground-handling, Engineers, Equipment manufac-turer						
311 Vehicle technical failure		0.26%	0.32%				
312 Radio communication		0.78%	1.92%	0.75%	0.34%		
313 Absence of a radar beacon							
314 Ground handling equipment					0.34%		
315 Tugs			0.16%				
316 Aerodrome meteorological equipment							
317 Vehicle/equipment design/							

manufacturing							
318 Vehicle/equipment improper maintenance							
317 Other							
32 V/PD - Human	V/PD, Airport authority						
321 Resources		1.43%	0.16%	1.49%		1.04%	
322 Competence		0.65%	0.80%	1.99%	0.74%		
326 Communication		2.99%	3.83%	1.99%	2.76%		
323 Situational awareness		0.13%	2.24%	0.49%	0.74%		
324 Human-machine interface		0.26%	0.32%				
325 Human reliability		22.02 %	19.80 %	18.76 %	19.65 %	3.13%	
327 Team operations		0.97%	0.48%	1.24%	1.03%		
328 Airport management			0.16%	0.49%	0.74%		
329 Airport operations		9.22%	1.12%	10.45 %	2.76%	1.04	
330 Procedures		0.39%	0.48%	2.23%	0.34%		
33 Airport Physical	Airport authority, Airport planner						
331 Airport design		0.91%	1.60%	3.23%	2.76%	1.04%	
332 Surface infrastructure and conditions		17.66 %	6.07%	42.78 %	18.97 %	3.13%	
4 Environment							
41 Weather	External influences						
411 Winds		1.30%	0.48%	0.49%			
412 Turbulence/Wake vortex							
413 Insufficient visual reference/ low visibility conditions		0.26%	0.16%				
414 Snow/Ice		0.65%		0.49%	1.03%		
415 Rain/aquaplaning							
416 Nice weather							
417 Other							
42 Geological disturbances							
43 Night time operations		0.13%					
44 Wildlife				0.24%			
45 External factors		1.82%		1%		1.04	
5 Regulatory system	Regulator						

Legend:

> 20.0% of causal factors fall into this category
Between 10.0 and 20.0% of causal factors fall into this category
Between 5.0 and 10.0% of causal factors fall into this category
< 5.0% of causal factors fall into this category

Table 10: Causal factors (Level 3) NZ

Causal factor	Responsibility	Database
		ASMS
1 Aircraft operations		
1 Aircraft - Technical	Airline, Engineers, Aircraft manufacturer, Ground-handling	2.69%
111 Aircraft technical failure		
112 Aircraft weight and balance		
113 Master caution warning		0.21%
114 Aircraft design/manufacturing		
115 Aircraft improper maintenance		
116 Environmental influences		
12 Pilot - Human	Pilot	
121 Resources		1.24%
122 Competence		2.69%
123 Communication		5.17%
124 Situational awareness		7.85%
125 Human-machine interface		1.03%
126 Human reliability		44.17%
127 Team operations		1.03%
128 Procedures		0.21%
2 ATC		
21 ATC - Technical	ANSP, Engineers, Equipment manufacturer	
211 Surveillance system		
212 Navigation system		
213 Communication system		
214 Equipment design/manufacturing		
215 Equipment improper maintenance		
22 ATC - Human	ATC	
221 Resources		
222 Competence		0.62%
226 Communication		1.45%
223 Situational awareness		6.41%
224 Human-machine interface		0.21%
225 Human reliability		10.74%
227 Team operations		0.62%
228 Procedures		0.41%
3 Airport operations		
31 Airport – Technical	Airport authority, Ground-handling, Engineers, Equipment manufacturer	
311 Vehicle technical failure		
312 Radio communication		
313 Absence of a radar beacon		
314 Ground handling equipment		
315 Tugs		
316 Airport meteorological equipment		
317 Vehicle/equipment design/manufacturing		
318 Vehicle/equipment improper maintenance		
319 Other		
32 V/PD - Human	V/PD, Airport authority	
321 Resources		0.21%
322 Competence		0.21%
326 Communication		0.83%
323 Situational awareness		
324 Human-machine interface		
325 Human reliability		2.89%
327 Team operations		

328 Airport management		0.41%
329 Airport operations		0.62%
330 Procedures		0.21%
33 Airport - Physical	Airport authority, Airport planner	
331 Airport design		0.21%
332 Surface infrastructure and conditions		3.51%
4 Environment		
41 Weather	External influences	
411 Winds		3.31%
412 Turbulence/Wake vortex		
413 Insufficient visual reference/low visibility conditions		0.21%
414 Snow/Ice		0.21%
415 Rain/aquaplaning		0.41%
416 Nice weather		
417 Other		
42 Geological disturbances		
43 Night time operations		
44 Wildlife		
45 External factors		
5 Regulatory system	Regulator	

Legend:

> 20.0% of causal factors fall into this category
Between 10.0 and 20.0% of causal factors fall into this category
Between 5.0 and 10.0% of causal factors fall into this category
< 5.0% of causal factors fall into this category

Appendix VI: Final Taxonomy

1 Aircraft operations
11 Aircraft - Technical
111 Aircraft technical failure
1111 Engine / power plants
11111 Engine
111111 Poor acceleration
11112 Thrust reverser
1112 Landing gear and breaking system
11121 Tires and wheels
111211 Brakes
111212 Anti-skid system
111213 Oleo strut
11122 Nose gear steering system
111221 Missing
111222 Malfunction
1113 Airframe
11131 Canopy
111311 Malfunction
111312 Flew off
11132 Doors
11133 Storage room hatch
11134 Windscreen
1114 Flight controls
11141 Wing
111411 Flaps
111412 Spoiler
111413 Ailerons
11142 Tail
11143 Rudder
1115 Air condition pressuring system
1116 Electrical system
1117 Hydraulic system
1118 Fuel system
1119 Avionics
11110 Navigation devices
11111 Computer system
111111 In-flight system (e.g. FMS)
111112 Airspeed indicator
11112 Automation system (e.g. autopilot)
11113 Communications system
111131 No radio
111132 No headset used
111133 Stuck microphone
111134 Poor radio contact
111135 Transmission completely or partially blocked
111136 Double transmission
11114 Cabin
111141 Technical problems in cabin
11115 Other
111151 Seats

111152 New technologies are not available to pilots

112 Aircraft weight and balance

1121 Fuel

11211 Forgotten

11212 Not enough

1122 Cargo

11221 Side load

1123 People

113 Master caution warning

114 Aircraft design / manufacturing

1141 Design short comings

1142 Necessary changes rejected by aircraft manufacturers due to costs considerations

1143 Lack of appropriate operational and performance information for operators that accounts for the spectrum of runway conditions they might experience

1144 Outdated technology

11441 Technology being ten years behind

11442 Technology not available to pilots

1145 Manufacturing defect

1246 Other

115 Aircraft improper maintenance

1151 Maintenance not conducted

1152 Inappropriate manintenance

11521 Failure not detected

1153 Engine ground run

1154 Other

116 Environmental influences

1161 Engine bird ingestion

1162 Other

117 Other

12 Pilot - Human

121 Resources

1211 Multi-tasking job

1212 Workload

1213 Pressure

12131 To be on time / not to loose a slot

12132 By being already delayed

12133 By other crew members

12134 By semi-annual check

1214 Fatigue

1215 Medical conditions

12151 Flying although feeling sick

1216 Other

122 Competence

1221 Training

12211 Insufficient

12212 In-flight training on going

1222 Inexperience

12221 First time flying into a controlled airport

1223 Pilot certification
12231 Missing
12232 Not renewed
12233 Maintenance engineer taxies the aircraft
1224 Other

123 Communication

1231 Contact establishment
12311 Pilot missed ATC calls
12312 Pilot failed to contact ATC when required
123121 No initial contact to ATC to ask for clearance (pilot never contacted ATC)
123122 Pilot failed to contact ATC as required after an initial contact had been made (pilot was in contact with ATC but failed to report as required)
123123 Pilot failed to inform ATC when he/she could not comply with a clearance
123124 Pilot did not advise ATC of a delay on the runway prior to take-off
12313 Use of incorrect frequency
123131 Pilot did not switch to the right frequency / frequency confusion
123132 Pilot did not know the frequency of the concerned airport
1232 Phraseology
12321 Non-English language
12322 Non-standard ICAO phraseology
12323 Articulation
123231 Poorly enunciated / heavily accented
123232 Rapidly spoken
1233 Communication process
12331 Pilot statements to ATC
123311 Incorrect statement
123312 Incorrect position report
12332 Instructions from ATC and other parties
123321 Misunderstanding of ATC instructions
123322 Acceptance of ATC instructions for another party / call sign confusion
1233221 Aircraft
1233222 V/PD
123323 Acceptance of instructions from a party other than ATC
1233231 Pilot following the instructions of another pilot from another aircraft
12333 Read back
123331 Incorrect
123332 Only reading back part of the instructions
123333 Not conform to the issued clearance
123334 Correct, followed by an unauthorized manoeuvre
123335 No read back
12334 Clarifications
123341 Not asking for clarifications when pilot did not understand ATC instructions

123342 Not asking for clarification when pilot realized ATC instructions are wrong / ambiguous
123343 Not asking for clarification when pilot is unsure about something (in general)
12335 Other

124 Situational awareness

1241 Flight operations
12411 Forgetting / confusion
124111 Clearances
1241111 Forgetting to ask for clearance
1241112 Forgetting a clearance the pilot had received
1241113 Forgetting part of a clearance the pilot had received
1241114 Confusion / unsureness about a clearance the pilot had received
124112 Airport operating mode
1241121 Pilot thought the tower was closed
1241122 Pilot thought the tower would be open when it was closed
1241123 Pilot thought the airport is uncontrolled
1241124 Pilot expected another type of CAT operations (e.g. CAT I instead of III)
1241125 Pilot not being aware about a closed runway
124113 Other
12412 Distraction
124121 Head down task
1241211 Checklist
1241212 FMGS
1241213 Due to a technical problem
124122 No sterile flight deck
1241221 Coordination with cabin crew
1241222 Announcements to passengers
124123 Conversations in cockpit
124124 Concentration / focusing
124125 By another aircraft
124126 First officer training
124127 License validation check
124128 Medical emergencies in the cabin
124129 Other
12413 Inattention
1242 ATC
12421 Last minute changes of
124211 Taxi routes
124212 Departure / arrival runway
124213 SID / STAR
12422 Use of non-standard taxi routes
12423 ATC using non-English language with other aircraft, which affects the situational awareness of the concerned crew
12424 Other
1243 Airport
12431 Familiarity

124311 Familiar
1243111 Complacency
1243112 Pilot had flown the same route already several times and assumed ATC would give him the same taxi route as used previously
124312 Unfamiliar
1243121 Temporary layout changes of the manoeuvring area
1243122 New layout configuration (permanently)
1243123 Difficulties to identify the displaced threshold
1243124 Holding point expected in another location
12432 Disorientation
124321 Pilot landed / departed
1243211 On a wrong runway
1243212 From a taxiway
1243213 On the wrong airport
1243214 On a closed airport
124322 Pilot confused runway edge lights with centerline lights and tried to depart along the edge
124323 Pilot confused a taxiway with a runway
124324 Crew orientated themselves on what another aircraft did and thought it would apply for them as well
12433 Airport charts
124331 Missing / not using
124332 Inaccurate / out of date / information missing
124333 Up to date charts, but crew uses old ones
124334 Unreadable
124335 Ambiguous statements on charts / confusing charts
12434 ATIS
124341 Pilot did not listen to ATIS
124342 Misunderstanding of ATIS
124343 NOTAM
1243431 Pilot did not read the NOTAM
1243432 Misunderstanding of NOTAM
12435 Other
1244 Aircraft
12441 Unfamiliarity
12442 Other
1245 Personal
12451 Daydreaming / mind on other things / taking personal problems to work
12452 Other
1246 Other

125 Human-machine interface

1251 Incorrect selection on instruments
1252 Radio
12521 Radio switched off
12522 Pilot turned down the volume of the radio
12523 Pilot did not plug in his headset properly
1253 Other
12531 Use of nosewheel-steering tiller at airspeeds that are too fast

12532 Failure to arm ground spoilers
12533 Pilot inadvertently applied pressure to the ruder pedals
12534 Pilot did not push prop control

126 Human reliability

1261 Planning
12611 Inadequate aircraft check
12612 Improper planning of ground operations
12613 Aircraft weight calculation error
12614 Taxi route not briefed
12615 Improper checklist use
12616 Other

1262 Action
12621 With clearance
126211 Slow / delayed action
126212 Non-compliance with ATC instructions / clearances
1262121 Willful

12622 Without clearance
126221 Pushback
126222 Taxiing
1262221 Entering area without clearance
12622211 Runway
12622212 Taxiway / taxi error
12622213 Pilot used the manoeuvring area before the airport was open

1262222 Not stopping at the required position
12622221 In front of a runway (hold line)
12622222 On a taxiway

126223 Take-off
126224 Landing
126225 Other
1262251 Pilot simply followed another aircraft

126226 Non-flight related
1262261 Pilot wanted to pick up things on the runway/taxiway (e.g. signage / FOD)

1263 Execution
12632 Taxi phase
126321 Pilot started taxiing while handling crew was still on the taxiway and not clear of the aircraft
126322 Pilot did not check whether the area is clear of obstacles and other traffic
126323 Taxi speed too high
126324 Pilot did not break in time
126325 Inappropriate use of power / jet blast
126326 Inappropriate turns
1263261 Turn too wide
1263262 No turn
1263263 Aircraft slides during turn
1263264 During a turn on the taxiway a wing infringed the adjacent runway
1263265 Pilot cutting corners

126327 Pilot taxied around another aircraft / vehicle that blocked the taxiway
126328 Aircraft route deviation / excursion
1263281 Pilot leaving the taxiway and going straight to the destination (e.g. over grassland)
1263282 Aircraft leaving the paved surface with one wheel
1263283 Deviation from centerline
1263284 Loss of control during taxiing
126329 Aircraft collision
1263291 With equipment/infrastructure
1263292 With another aircraft
1263210 Other
12633 Take-off
126331 Directional control
126332 Thrust asymmetry
126333 Rotation
1263331 No rotation
1263332 Before V_R[35]
126334 Ground loop
126335 Unable to take-off within available / remaining runway length
126336 Rejected take-off
1263361 Initiated at a speed greater than V1[36]
1263362 Before V1 is reached
1263363 Not considered
126337 Loss of control in take-off
126338 Brakes mistakenly applied
126339 Loss of control over rudder pedals
1263310 Pilot did not check whether the area is clear of obstacles or other traffic
1263311 Pilot failed to detect the changing wind/weather conditions
1263312 Other
12634 In-flight
126341 Pilot failed to detect the changing wind/weather conditions
126342 Loss of control in flight
126343 Other
12635 Approach / landing
126351 Directional control
126352 Unstabilized approach/landing
1263521 Approach
12635211 Path/glide slope deviation
12635212 Fast
12635213 High
12635214 Below safe attitude
12635215 Sudden sink during short final
12635216 Incorrect assessment of landing distance / required runway length

[35] V_R is the rotation speed
[36] V1 is the decision speed, i.e. the maximum speed at which a rejected take-off can be initiated in the event of an emergency (Airbus, 2004d)

12635217 Go-around not conducted
12635218 Forgetting to extend landing gear
12635219 Pilot technique inappropriate for prevailing meteorological conditions
126352191 In crosswinds
126352192 Downwind landings
126352110 Pilot raised flaps on short final
126352111 Inappropriate speed control
126352112 Rudder control
1263521121 Too much rudder control / excessive use / overcompensation
1263521122 Application of wrong rudder
1263521123 Loss of rudder control
126352113 Inappropriate flare
126352114 Aircraft struck object on final approach
126352115 Other
1263522 Landing / touchdown
12635221 Long
12635222 Fast
12635223 Hard
12635224 Bouncing
12635225 Off-centre
12635226 Short
12635227 Failure to observe a reasonable distance to land behind another aircraft
12635228 Tail / propeller / other aircraft parts strike
12635229 Other
126353 After touchdown
1263531 Incorrect perception of speed
1263532 Late / incorrect use of thrust reverser
1263533 Braking
12635331 Inappropriate
126353311 Too excessive
126353312 Late
126353313 Auto-break use not adequate
126353314 Pilot could not reach the breaks
12635332 Ineffective
126353321 Due to runway contamination
126353322 Other
1263534 Pilot does not vacate the runway quickly enough
1263535 Aircraft could not vacate runway completely due to other traffic in front of the aircraft
1263536 High-speed acceleration stop manoeuvre
1263537 Pilot overreaction
12635371 In general
12635372 While trying to overcome the tendency of the aircraft to veer
12635373 Oversteering
1263538 Aircraft route deviation / excursion
12635381 Deviation from runway

12635382 Pilot allowed aircraft to veer
12635383 Aircraft became off-centre
12635384 Pilot allowed nose to veer to one side (one wing dropped)
12635385 Ground loop
12635386 Loss of control on runway
126353861 Due to another aircraft still being on the runway
12635387 Loss of control during runway exit
12635388 Pilot could not stop in the remaining runway distance
12635389 Aircraft became disabled in runway safety area
1263539 Other
12636 Pilot misperception / misjudgment
126361 Incorrect assumptions concerning clearances (pilot being sure about a clearance that was not issued)
1263611 Pilot believed to have the same clearance as a couple of days before
1263612 Pilot assumed that a prior issued clearance is still valid
1263613 Misinterpretation - Pilot gets VFR clearance and assumes he/she got departure clearance
1263614 Pilot did not realize a condition in the clearance
126362 Pilot did not expect holding point in this position
126363 Misinterpretation / misjudgment of distances at the airport
126364 Misjudgment of distance to a landing aircraft
126365 Pilot not aware of the implications of a reduced runway length
126366 Underestimation of runway downslope
126367 Misjudgment of breaking coefficient
126368 Pilot expected to get another parking position and taxi route
126369 Pilot misunderstood the intentions of another aircraft
1264 Other
12641 Pilot did not want to pay landing fees

127 Team operations

1271 Crew Resource Management (CRM)
1272 Improper Cross check / Coordination
1273 Inadequate pilot-in-command supervision of first officer
1274 Flight instructor – student
12741 Student pilot misunderstanding of flight instructors instructions
12742 Non-compliance with flight instructors instructions
1275 Other

128 Procedures

1281 Inadequacy
12811 Necessary instructions are not in the pilots handbook / flight manual contained poor instructions
12812 Aircraft manufacturer did not promulgate adequate procedures
1282 Misapplication
12821 Non-compliance

12822 Misunderstanding
1283 Other

2 ATC
21 ATC - Technical
211 Surveillance system
2111 Not existent
2112 Total failure
2113 Inconsistent signal
212 Navigation system
213 Communication system
2131 Communication breakdown
21311 ATC – Aircraft
21312 ATC – V/PD
2132 Stuck microphone
2133 Transmission completely or partially blocked
2134 Double transmission
214 Equipment design / manufacturing
2141 Inadequate equipment design
21411 Integration of different systems
215 Equipment improper maintenance
216 Other

22 ATC - Human
221 Resources
2211 Complex task / multi-tasking job
2212 Workload
22121 Lack of vigilance, inattentiveness, and boredom during periods of low workload
2213 Time pressure
2214 Fatigue
2215 Tower staffing problem / shortage of ATC
2216 Other
222 Competences
2221 Training
22211 Insufficient training
22212 Trainee not confident enough to challenge the air crew
2222 Inexperience
2223 Other
223 Communication
2231 Phraseology
22311 Non-English language
22312 Non-standard ICAO phraseology
22313 Articulation
223131 Over complex, rapidly spoken
223132 Ambiguous
223133 Badly enunciated
223134 Different accents
22314 Omission of one or more steps
22315 Issue to a wrong party

223151 Aircraft
223152 V/PD
22316 Other
2232 Communication process
22321 Instructions / statements received by ATC
223211 Misunderstanding
22322 Read back
223221 ATC acknowledgment (of the read back of another party)
2232211 Incorrect
2232212 Not conform to the requested clearance/subject
2232213 No acknowledgment
2232214 Other
223222 Read back from another party (pilot / V/PD)
2232221 ATC did not ensure that the read back conforms to the clearance issued
2232222 ATC did not correct errors in a received read back
2232223 ATC did not obtain read back at all
2232224 ATC thought the read back is correct while it was incorrect
22323 Clarifications
223231 Not asking for clarification when ATC id not understand the pilot / V/PD
22324 Other
2233 Other
22331 Misperception of information ATC issues
223311 Misperception of clearance content / ATC believing it issued another clearance
22332 Misperception of information ATC receives
223321 Misperception of message content / ATC believing pilot / V/PD said something he did not say
22333 Busy communications with a lot of coordination
22334 Use of similar call signs
22335 Frequencies
223351 Use of multiple frequencies leading to confusion
223352 Busy frequencies / frequency congestion
223353 More than 1 ATC position combined on 1 frequency

224 Situational awareness

2241 ATC operations
22411 Forgetting / confusion
224111 ATC forgetting aircraft position
2241111 On approach to land
2241112 That an aircraft had already landed
2241113 On runway
2241114 On taxiway
224112 ATC forgetting V/PD position
2241121 On runway
2241122 On taxiway
224113 ATC forgetting clearance
2241131 To issue a clearance
2241132 That a clearance has been issued

- 22411321 To take-off
- 22411322 To land
- 22411323 For crossing
- 224113231 A runway
- 224113232 A taxiway
- 2241133 Limits of the issued clearance
- 224114 ATC forgetting closures
- 2241141 Of a runway
- 2241142 Of a taxiway
- 224115 Confusion of two aircraft/vehicles
- 224116 Other
- 22412 Distraction
- 224121 Traffic processing
- 2241211 Inputting flight data
- 2241212 Coordination over the telephone
- 2241213 On-the job training
- 2241214 Handover
- 224122 Duties other than traffic processing
- 2241221 Operational
- 22412211 Weather observations and recording
- 22412212 Telephone calls
- 22412213 Other
- 2241222 Non-operational
- 22412221 Conversations
- 22412222 Telephone calls
- 22412223 Reading material
- 22412224 Visitors in the tower
- 22412225 Administrative duties
- 22412226 Other
- 22413 Inattention
- 2242 Airport
- 22421 ATC not aware of recent configuration changes (runway / taxiway)
- 22422 View on the manoeuvring area from ATC tower
- 224221 Limited view from ATC tower
- 224222 Lack of visual scanning
- 2242221 Lack of visual scanning, because ATC monitors the cameras that allow him / her to see parts of the manoeuvring area that are not visible from the tower
- 22423 Other
- 2243 Personal
- 22431 Daydreaming / mind on other things / taking personal problems to work
- 22432 Bad relationships with colleagues
- 22433 ATC attitude / behavior
- 22434 Other
- 2244 Other

225 Human-machine interface

- 2251 Misused equipment
- 2252 Other

226 Human reliability

2261 Non, or inaccurate provision of information
- 22611 ATC services
  - 226111 ATC not in tower, doing a break
- 22612 Wind weather information
  - 226121 Not in time
  - 226122 Not accurate
- 22613 Runway condition information
  - 226131 Not in time
  - 226132 Not accurate
- 22614 Information of work on the manoeuvring area
- 22615 Taxi routes
  - 226151 No use of standard taxi routes
  - 226152 No use of progressive taxi instructions
- 22616 Information about safety challenging situations
- 22617 ATIS not up to date
- 22618 Other

2262 Incorrect / inadequate instructions / clearances
- 22621 For take-off
- 22622 For approach / landing
  - 226221 Failure to descent the aircraft appropriately
  - 226222 Failure to allow aircraft the appropriate approach speed
  - 226223 Issuing clearance to land on a runway although another runway would have been preferential
    - 2262231 Breaking coefficient
    - 2262232 Wind
    - 2262233 Runway length
- 22623 Wrong instructions issued
- 22624 Last minute changes of instructions
  - 226241 Taxi routes
  - 226242 Departure / arrival runway
  - 226243 SID / STAR
- 22625 Clearance to use inappropriate / unsafe surfaces
- 22626 Clearance given too early
- 22627 Conflicting clearances
- 22628 Conditional clearance
  - 226281 With wrong condition
  - 226282 Given too early
- 22629 Line up clearance that requires an aircraft to hold on the runway for more than 90sec
- 226210 Clearance given to a bunch of vehicles
- 226211 ATC giving instructions during high periods of workload (e.g. short final)
- 226212 Other

2263 Misidentification/misjudgment
- 22631 Position (Aircraft / V/PD)
- 22632 Miscalculation of the required separation
- 22633 Misinterpretation / misjudgment of the aircraft performance
- 22634 Misjudgment of timings that led to a situation that was too tight

2264 Other
- 22641 ATC did not check if the aircraft had effectively cleared the runway

22642 ATC not using flight strips
22643 Mishandling of flight strips
22644 Mishandling of traffic lights
22645 ATC gives the pilot a hard time when requesting Marshalls

227 Team operations

2271 Inadequate teamwork
22711 Coordination
22712 Handover
22713 Issue of conflicting clearances
2272 Supervision
22721 Inadequate supervision
22722 Absence of a supervisor in the tower when situation required one
2273 One controller covering more than one position
2274 Other

228 Procedures

2281 No procedures in place
22811 No standard taxi practices exist
2282 Inadequacy
22821 Inadequate clearance procedures
22822 ATC agreement between 2 airports was not documented properly
22823 Provision of taxi routes to the pilots only after the aircraft touched down
2283 Misapplication
22831 Non-compliance
228311 Willful
228312 Not willful
22832 Misunderstanding
2284 Other

3 Airport operations

31 Airport - Technical

311 Vehicle technical failure

312 Radio communications

3121 No radio
3122 Radio technical failure
3123 Discharged battery
3124 Poor radio contact
3125 Stuck microphone
3126 Double transmissions
3127 Two airports turning into each other's frequencies
3128 Communication problems due to new equipment

313 Absence of radar beacon on the vehicle

314 Ground handling equipment (cargo dollies, baggage carts, etc.)

3141 Locking device – equipment breaking loose

315 Tugs

3151 Tug connecting element – aircraft got disconnected

316 Airport meteorological equipment

317 Vehicle / equipment design / manufacturing

318 Vehicle / equipment improper maintenance

319 Other

32 V/PD - Human

321 Resources

- 3211 Workload
- 3212 Fatigue
- 3213 Medical conditions
- 3214 Work attitude
  - 32141 Ambition
    - 321411 Eagerness to solve a safety-challenging situation
    - 321412 Wanting to be efficient / proceeding with a new task
    - 321412 Helpful / wanting to help colleagues
- 3215 Other

322 Competences

- 3221 Training
  - 32211 No training
  - 32212 In-training (e.g. flying school)
  - 32213 Inadequate training
- 3222 Inexperience
- 3223 Other

323 Communications

- 3231 Communication V/PD with ATC
  - 32311 Contact establishment
    - 323111 V/PD missed ATC calls
      - 3231111 Person physically too far away from the radio
    - 323112 V/PD failed to contact ATC when required
      - 3231121 No initial contact to ATC to ask for clearance (V/PD never contacted ATC)
      - 3231122 V/PD failed to contact ATC as required after an initial contact had been made (V/PD was in contact with ATC but failed to report as required)
      - 3231123 Not contacting ATC immediately after a vehicle technical problem occurred
    - 323113 V/PD use of incorrect frequency / frequency confusion
    - 323114 V/PD contacts tower, but does not await a reply
  - 32312 Phraseology
    - 323121 Non-English language
    - 323122 Non-standard ICAO phraseology
    - 323123 Articulation
  - 32313 Communication process
    - 323131 V/PD statements to ATC
      - 3231311 Incorrect statement
      - 3231312 Incorrect position report
    - 323132 Instructions from ATC
      - 3231321 Misunderstanding
      - 3231322 Acceptance of instruction for another party / call sign confusion
        - 32313221 V/PD
        - 32313222 Aircraft
    - 323133 Read-back
      - 3231331 Incorrect
      - 3231332 Not conform to the issued clearance

3231333 Correct, followed by an unauthorized manoeuvre
3231334 No read back
323134 Clarifications
3231341 Not asking for clarification when V/PD did not understand ATC instructions
3231342 Not asking for clarification when V/PD realized ATC instructions are wrong/ambiguous
323135 Other
3232 Communication V/PD with pilot
3233 Communication between V/PDs
32331 Miscommunication between escort vehicle and following vehicle

324 Situational awareness

3241 V/PD operations
32411 Forgetting / confusion
324111 V/PD forgetting details / limits of a clearance
324112 V/PD confused an escort vehicle with another car
324113 V/PD thought the tower is closed
324114 V/PD thought a runway / taxiway is closed
324115 Other
32412 Distraction
324121 Current work
324122 V/PD watching / focusing on other aircraft/V/PD
324123 Monitoring more than one frequency
324124 Mobile phone
324125 Noise level
324126 Other
32413 Inattention
3242 Airport
32421 Unfamiliarity
32422 Disorientation
32423 Lack of knowledge
324231 About aerodrome signs and markings
324232 Where safety area starts
32424 Airport charts
324241 Missing/not using
324242 Inaccurate/out of date
32425 Not referring to the current NOTAM
32426 Other
3243 Personal
32431 Daydreaming / mind on other things / taking personal problems to work
32432 Other
3244 Other

325 Human-machine interface

325 Radio
3251Radio switched off
3252 V/PD turned radio off / to a lower volume after initial communication with ATC
326 Other

326 Human reliability

- 3261 Action
  - 32611 Action with clearance
    - 326111 Slow / delayed action
    - 326112 Non-compliance with ATC instructions
  - 32612 Action without clearance
    - 326121 Incorrect parking
      - 3261211 Parking on the line that separates apron and manoeuvring area
      - 3261212 Blocked clearway
      - 3261213 Obstacle for landing aircraft
      - 3261214 Handling equipment parked inappropriately
    - 326122 Pushback
      - 3261221 Pushback without clearance
      - 3261222 Long pushback / pushback on taxiway
    - 326123 Taxiing
      - 3261231 Entering area without clearance
        - 32612311 Runway
        - 32612312 Taxiway
        - 32612313 Manoeuvring area – unknown
      - 3261232 Not stopping at the required position on runway / taxiway (e.g. hold line, stop bar)
    - 326124 Pedestrians / bicyclists
      - 3261241 Unintended penetration of the manoeuvring area
        - 32612411 Person unaware that access to the manoeuvring area is not allowed
        - 32612412 Person assuming that entering the manoeuvring area is allowed after the tower is closed
        - 32612413 Person running out to make pictures of a landing aircraft
        - 32612414 Aircraft maintenance crew entering manoeuvring area
      - 3261242 Willful penetration of the manoeuvring area
- 3262 Execution
  - 32621 Groundhandling
    - 326211 Operator started ground handling while engines still running
    - 326212 Aircraft being insufficient secured and starting to roll
    - 326213 Incooperative groundhandling personnel
    - 326214 Other
  - 32622 V/PD driving style
    - 326221 V/PD disregarded traffic rules
    - 326222 V/PD did not give way to preceding traffic
    - 326223 V/PD overtaking slower vehicles and infringing the manoeuvring area
    - 326224 V/PD driving too close to other traffic
    - 326225 V/PD driving too fast
    - 326226 V/PD ignoring runway/taxiway signs
    - 326227 V/PD cutting corners
    - 326228 V/PD avoiding action (not to collide with other traffic)
    - 326229 Other
  - 32623 V/PD route deviation / excursion

326231 Loss of control over vehicle
326232 V/PD hits airfield infrastructure during surface operations
32624 V/PD Misperception / misjudgment
326241 V/PD assumed a promise for a future clearance is automatically a clearance
326242 V/PD acts according to an old clearance assuming it is still valid
326243 V/PD expected that he got the clearance he requested and failed to notice that he had received another clearance
326244 V/PD expected ATC would know the route he was taking
326245 Other
32625 Other

327 Team operations

3271 Authorised airfield escort
32711 Escort did not ensure that all V/PD vacated the runway when confirming to ATC
32712 Escort did not obtain clearance for all vehicles under his/her responsibility
32713 Escort did not ensure that all cleared vehicles are together, some vehicles running behind
32714 V/PD simply followed an authorized escort without having clearance
3272 Inadequate supervision
32721 V/PD not being adequately briefed at shift start
3273 Operational personnel not following supervisor's instructions
3274 Missing communication between two team members
3275 Other

328 Procedures

3281 Inadequate procedures
32811 Airport operator published unsafe procedures / inadequate guidelines in place
32812 Outside airport opening hours procedures
32813 Procedures for construction / maintenance work
32814 Winter maintenance procedures
32815 Emergency procedures
32816 Push-back procedures
32817 Procedures for free range operations
3282 Inadequate implementation - New procedures not being passed on to the relevant personnel
3283 Procedures were not changed after a problem had been discovered
3284 V/PD not following procedures
3285 Capacity enhancing procedures
3286 Other

329 Airport management

3291 Inappropriate obstacle assessment
3292 No or inadequate risk assessment for procedural and/or infrastructural changes
3293 No clear decision and communication whether a taxiway belongs to the apron or manoeuvring area and a clearance is required
3294 Lack of communication and coordination between two parties at the airport
3295 Security

32951 Fencing
329511 Inappropriate/defect
3295111 For animals - animals jumping over fences, coming through holes in fences
3295112 For people – people jumping over fences, children crawling underneath, etc.
329512 Snowed under
32952 Airport security gate
329521 Open
329522 Faulty
93743 Perimeter road not adequately secured
3296 Other

3210 Airport operations

32101 Runway operations
321011 Multiple runway operations
3210111 Crossing
3210112 Closely spaced parallel
321012 Runways used as taxiways
321013 Aircraft must backtrack on runway
321014 Runway operated at reduced length
321015 Runway not closed when conditions dictated
321016 Failure to allow use of wind-preferential runway
32102 NOTAM
321021 Runway closure not advised by NOTAM
321022 Work on the manoeuvring area not advised by NOTAM
32103 Information about temporary work areas not adequately disseminated
32104 Provision of incorrect surface condition information deliberately
32104 New temporary tower in operation
32105 Maintenance / construction work
321051 Improper maintenance
3210511 Maintenance personnel forgetting tools, etc.
3210512 Maintenance personnel working sloppily
3210513 Use of inadequate materials
32105131 Use of wrong materials, because correct ones were out of stock
32105132 Bad quality supplies
321052 Poor housekeeping
3210521 Deterioration of infrastructure
3210522 Inadequate inspections / audits
3210523 Irregular inspections / audits
32106 Surface inspection / FOD removal
32107 Snow removal
32108 Grass cutting
32109 Emergency vehicles in operation / emergency exercise
321010 Wildlife management
3210101 Shooting
321011 Low visibility procedures
321012 Towing
321013 Technical help for an aircraft that broke down
321014 Aircraft marshaled incorrectly

321015 Training exercise
321016 Security
3210161 Security inspection (e.g. fencing)
3210162 No security measures in place after they had been requested
3210163 Visitors left unattended
321017 Traffic
3210171 Traffic volume
3210172 Traffic mix
3210173 Unexpected traffic (e.g. emergency / ambulance flights)
321018 Other

33 Airport - Physical
331 Design
3311 Airport location and surrounding land use
33111 Forest and vegetation
33112 Residential areas
33113 Industry
33114 Landfill / waste / composting facilities
33115 Agriculture / fields
331151 Crops
331152 Livestock
33116 Water sources
33117 Fishing
33118 Entertainment facilities
33119 Other
3312 Airport landscaping
33121 Water sources
33122 Grassland
33123 Bushes / trees
33124 Wildlife shelter
33125 Other
3313 Manoeuvring area design
33131 Complex runway / taxiway layout
331311 Rapid exit taxiway
331312 Angled intersections to enter the runway
331313 Insufficient spacing between parallel runways
331314 Intersecting runways
331315 Crossing of multiple active runways necessary to get to the desired destination
33132 Unusual layout
33133 Hotspot
33134 Runway-specific design
331341 Runway surface construction and slope
331342 Inadequate runway safety areas
33135 Apron design
331351 Insufficient spaces for the operations
33136 Construction area
331361 Temporary layout changes
331362 Temporary signs / markings are inadequate
331363 Work in progress (WIP) limits the view from the tower

331364 Barriers to mark WIP are too close to a runway / taxiway
331365 New permanent manoeuvring area configuration
33137 Other
332 Surface infrastructure and conditions
3321 Runway
33211 Lighting
332111 Not provided
332112 Inadequate / confusing
332113 Not working / not in use
332114 Timer function switches on stop bars automatically after 90 seconds
33212 Markings / Signage
332121 Not provided
332122 Inadequate / Non-ICAO compliant
332123 Confusing
332124 With snow covered / difficult to see
332125 Hold line not visible from cockpit
332126 Not well maintained (e.g. erased lines, signs unreadable)
332127 Signs in unusual position
332128 Markings are poorly lit
332129 Irregular spaced
3321210 Recent changes
33213 Approach / landing aid
33214 Surface conditions
332141 Contamination
332142 Slippery runway
332143 Concrete cracks, dips, humps, ruts in runway
332144 FOD
3321441 Wildlife remains
3321442 Vehicles / equipment operating on the surface
3321443 Construction debris
3321444 Tools / small parts (e.g. screws)
3321445 Concrete, asphalt, joint filler (pavement)
3321446 Runway infrastructure (e.g. lights)
3321447 Personal belongings of passengers and employees
3321448 Aircraft parts
33214481 Wheels/tire
33214482 Engine
33214483 Door / hatch
33214484 Window
33214485 Canopy
33214486 Communication antenna
33214487 Other aircraft parts
3321449 Environmental (e.g. gravel, sand, stones, parts of trees)
33214410 Other parts / debris on the runway
332144101 Baggage tags, loading documents, other paper
332144102 Plastics / packing materials
332144103 Garbage / rubbish bags

332144104 Glass
332144105 Bags / luggage / freight
332144106 Handling equipment (e.g. chocks, cones, ULD container)
332144107 Rubber
332144108 External (pieces not found at an airport, e.g. graveyard lights, golf balls)
332145 Other
33215 Other
3322 Taxiway
33221 Lighting
332211 Not provided
332212 Inadequate / confusing
332213 Not working / not in use
33222 Markings/signage
332221 Not provided
332222 Inadequate / non-ICAO compliant
332223 Confusing
332224 With snow and ice covered
332225 Other
33223 Surface conditions
332231 Contamination
332232 Slippery taxiway
332233 Concrete cracks, dips, humps, ruts in runway
332234 FOD
3322341 Wildlife remains
3322342 Vehicles / equipment operating on the surface
3322343 Construction debris
3322344 Tools / small parts (e.g. screws)
3322345 Concrete, asphalt, joint filler (pavement)
3322346 Runway infrastructure (e.g. lights)
3322347 Personal belongings of passengers and employees
3322348 Aircraft parts
3322349 Environmental (e.g. gravel, sand, stones, parts of trees)
33223410 Other parts / debris on the runway
332234101 Baggage tags, loading documents, other paper
332234102 Plastics / packing materials
332234103 Garbage / rubbish bag
332234104 Glass
332234105 Bags / luggage / freight
332234106 Handling equipment (e.g. chocks, cones, ULD container)
332234107 Rubber
332234108 External (pieces not found at an airport, e.g. graveyard lights, golf balls)
332235 Other
33224 Other
3323 Manoeuvring area

33231 Limits of the manoeuvring area not visible due to snow and ice

4 Environment
41 Weather
411 Winds
4111 Wind sheer / gusts / other winds
4112 Cross winds
4113 Thunderstorm
4114 Tailwind
412 Turbulences/wake vortex
4121 Turbulence
4122 Wake vortex
413 Insufficient visual reference/low visibility conditions
4131 Reflecting sun
4132 Fog/haze
414 Snow / ice
415 Rain / aquaplaning
416 Nice weather
417 Other
42 Geological disturbances
43 Nighttime operations
44 Wildlife
441 Wildlife dragging FOD on the manoeuvring area
45 External factors
451 Human
4511 People feeding birds
4512 Mentally sick person
4513 Other people (pedestrians, children, etc.)
4514 Passenger
45141 Passenger chasing lost items
45142 Crazy passenger
452 Other

5 Regulatory system
51 Regulations not existent
52 Regulations inadequate
53 Regulations existent, but not implemented

Appendix VII: Questionnaire Survey

Imperial College London

Lloyd's Register Educational Trust

Airport Characteristics Questionnaire

Dear Sir/Madam,

I am a Ph.D. research student in the department of Civil and Environmental Engineering at Imperial College London and I am trying to develop a new categorisation of airports, based upon certain factors related to safety. I want to investigate the impact of different airport characteristics (e.g. airfield geometry, equipment, operations) on the occurrence of accidents and incidents on the airport surface (manoeuvring area) by correlating these characteristics to safety data. Based upon that information a new airport categorisation will be proposed.

This questionnaire survey is aimed at gathering some of the information about the different airport characteristics that might impact on surface safety. Other characteristics, such as e.g. airfield geometry, are investigated using data provided by the FAA. The FAA also provided accident and incident data.

Such an airport categorisation in terms of safety would benefit airports by providing a tool kit that allows classification of airports into different safety-critical categories, in order to provide recommendations on how to improve the safety level for each of the categories.

I hope you will take a few minutes to complete the enclosed questionnaire. The questionnaire is designed to include only aspects that should be easy to determine for any airport operator, as otherwise such a categorisation would never be used. The questionnaire should not take longer than 10 minutes to complete.

The questionnaire is created in Microsoft® Word. It is my intention to enable you to fill it out electronically and directly send it back to me by using the following e-mail address **s.wilke09@imperial.ac.uk**.

Please be assured that your responses will be held in the strictest confidence. I am interested in identifying clusters of airports and to describe their characteristics rather than determining the safety level of individual airports. If the results of this study are used for publication, no identifying information will be used.

Thank you in advance for your time and effort.

Sincerely,

Sabine Wilke

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Airport Characteristics Questionnaire

Airport name: ……

ICAO identifier: ……

1. Traffic characteristics

- Primary type of traffic handled at your airport. Please specify by choosing **ONE** of the following options:
  - □ Civil aviation, please specify further:
    - □ Scheduled air transport
      - □ International
      - □ Domestic > 2000 km (distance at your discretion)
      - □ Domestic < 2000 km (distance at your discretion)
    - □ General Aviation (GA)
      - □ International
      - □ Domestic > 2000 km (distance at your discretion)
      - □ Domestic < 2000 km (distance at your discretion)
  - □ Military.
- Peak number of operations during peak hours. Please specify: [37]

  ……
- Number of airlines that have their main base at the airport. Please specify:

  ……

2. Equipment and installations:

- In your opinion, are there situations when your landing system (e.g. precision approach system / non-precision approach system / visual approach) does not adequately support the operations based upon them? Please specify: [38]

[37] Please specify the maximum number of operations (arrivals and departures together) your airport handles during peak hours.

□ Yes

□ No

3. Visual aids for navigation (signage, markings, lighting):

- In your opinion, are there situations when the visual aids for navigation do not adequately support the operations based upon them? Please specify: [39]
  - □ Yes
  - □ No
- Have there been reports / complaints about confusing visual navigation aids? Please specify:
  - Lighting system:
    - □ Yes
    - □ No

    If yes, how many reports have been made within the last 5 years?
    - □ Less than 10
    - □ 10 to 30
    - □ More than 30
  - Markings:
    - □ Yes
    - □ No

    If yes, how many reports have been made within the last 5 years?
    - □ Less than 10
    - □ 10 to 30
    - □ More than 30
  - Signage:
    - □ Yes
    - □ No

    If yes, how many reports have been made within the last 5 years?
    - □ Less than 10

[38] This question refers to the adequacy of your equipment, for instance, is your ILS sufficient for the operations it is supposed to support (e.g. your airport is equipped with ILS category I, but you would need a higher category in order to operate appropriately).

[39] This question refers to the adequacy of your visual aids for navigation.

□ 10 to 30

□ More than 30

4. Operations / maintenance

- Are subcontractors working on the manoeuvring area? Please specify: [40]
  - □ Yes
  - □ No
- How often are runway condition checks undertaken? Please specify:
  Every …… hours.
- How is the manoeuvring area operated?
  - Are runways used as taxiways and under what conditions? Please specify:
    - □ Yes
    - □ No

    If yes, is it a standard procedure?
    - □ Yes
    - □ No
  - Do vehicle drivers need clearance to operate on the manoeuvring area? Please specify:
    - □ Yes, all of them
    - □ Yes, some of them
    - □ No
  - Are all vehicles that have access to the manoeuvring area equipped with radio communication? Please specify:
    - □ Yes, all of them
    - □ Yes, some of them
    - □ No
- How often does construction / maintenance work on the manoeuvring area take place? Please specify by choosing one of the following options:
  - □ Weekly
  - □ Monthly

[40] Subcontractors refer to all operational personnel that have access to the manoeuvring area (e.g. vehicle drivers, construction workers).

□ Every 2 - 3 month

□ Every 4 - 6 month

□ More than 6 month

5. Regulations

- Do you engage in pro-active safety assessments apart from the regulatory requirements (e.g. Part 139 Airport Certification)? Please specify:
  - □ Yes
  - □ No

6. Human aspects

- In your opinion, do you have the right level of staffing to run the airside operations of your airport? Please specify: [41]
  - □ Yes
  - □ Under-staffed
  - □ Over-staffed
- In your opinion, is your operational staffs adequately trained? Please specify:
  - □ Yes
  - □ No
- If applicable, do you think your subcontractors are adequately trained? Please specify:
  - □ Yes
  - □ No

Thank you for taking the time to answer these questions. Your time and participation are greatly appreciated.

[41] The question refers to the operational personnel that run the airfield (e.g. operational, maintenance, safety staffs).

Appendix VIII: Supplementary Analysis to Chapter 10

1 Analysis at the Aggregate Level

The following sections contain the results for the data analyses conducted at the aggregated level (i.e. U.S., UK, NO, NZ aggregated).

1.1 Normality Tests

The continuous variables were tested for normality using the Kolmogorov-Smirnov test for samples > 50, and the Shapiro-Wilk test for samples < 50. If the test statistic is significant ($p < .05$) then the data is non-normal. Table 1 shows the results of the normality tests for the aggregated data (U.S., UK, Norway, NZ).

Table 1: Normality tests – aggregated data

Variable	Complete data set			
	Kolmogorov-Smirnov Test		Shapiro-Wilk Test	
	Statistic	Sig.	Statistic	Sig.
Number of incursions (per 100,000 movements)	.350	.000	.423	.000
Number of excursions (per 100,000 movements)	.348	.000	.438	.000
Number of FOD (per 100,000 movements)	.342	.000	.532	.000
Average annual movements	.211	.000	.788	.000
Altitude	.294	.000	.521	.000
Peak number of operations	.193	.000	.757	.000
Number of runways	.263	.000	.781	.000
Number of taxiway segments	.228	.000	.790	.000
Number of Type 2 conflict points	.124	0.45	.947	.023
Number of Type 3 conflict points	.241	.000	.792	.000
Number of Type 4 conflict points	.268	.000	.739	.000
Number of Type 5 conflict points	.315	.000	.513	.000
Number of Type 6 conflict points	.486	.000	.280	.000
Number of Type 7 conflict points	.538	.000	.195	.000
Number of Type 8 conflict points	.536	.000	.122	.000
Total number of conflict points RWY-RWY	.427	.000	.470	.000
Total number of conflict points RWY-TWY	.232	.000	.775	.000
Total number of conflict points TWY-TWY	.215	.000	.809	.000
Total number of conflict points at the airport	.215	.000	.809	.000
Total number of segments in conflict with each other	.216	.000	.797	.000
Number of communication channels	.153	.004	.922	.002
Number of frequencies	.173	.001	.894	.000

On an aggregated level, the tested variables are non-normal.

1.2 Data Homogeneity Tests

The data was tested for homogeneity and its consequent potential for aggregation. The appropriate statistical tests have been introduced in Chapter 10 section 10.2.10.4. Table 2 contains the test statistics based upon the complete data set (including outliers). Variables that could be aggregated ($p > .05$) across countries are highlighted in grey.

Table 2: Homogeneity tests

Variable	All 4 countries aggregated	North America vs. Europe	Norway vs. UK
Number of incursions (per 100,000 movements)	$H(3) = 35.47$, p (2-tailed) < .001	$U = 21.00$, p (2-tailed) < .001	$U = 47.00$, p (2-tailed) < .05
Number of excursions (per 100,000 movements)	$H(3) = 20.18$, p (2-tailed) < .001	$U = 178.50$, p (2-tailed) < .05	$U = 57.50$, p (2-tailed) < .05
Number of FOD (per 100,000 movements)	$H(3) = 20.81$, p (2-tailed) < .001	$U = 94.50$, p (2-tailed) < .001	$U = 72.50$, p (2-tailed) > .05
Critical factors (Taxonomy level 1)	$X^2 = 303.83$, p (2-tailed) < .001	$X^2 = 96.64$, p (2-tailed) < .001	$X^2 = 181.55$, p (2-tailed) < .001
Average annual movements	$H(3) = 32.01$, p (2-tailed) < .001	$U = 44.00$, p (2-tailed) < .001	$U = 29.00$, p (2-tailed) < .001
Altitude	$H(3) = 2.74$, p (2-tailed) < .05	$U = 207.00$, p (2-tailed) > .05	$U = 81.00$, p (2-tailed) > .05
Peak number of operations	$H(3) = 28.77$, p (2-tailed) < .001	$U = 29.00$, p (2-tailed) < .001	$U = 33.00$, p (2-tailed) < .05
Number of runways	$H(3) = 28.09$, p (2-tailed) < .001	$U = 50.50$, p (2-tailed) < .001	$U = 91.50$, p (2-tailed) > .05
Number of taxiway segments	$H(3) = 26.80$, p (2-tailed) < .001	$U = 51.50$, p (2-tailed) < .001	$U = 64.50$, p (2-tailed) < .05
Number of Type 2 conflict points	$H(3) = 27.43$, p (2-tailed) < .001	$U = 49.00$, p (2-tailed) < .001	$U = 64.00$, p (2-tailed) < .05
Number of Type 3 conflict points	$H(3) = 24.34$, p (2-tailed) < .001	$U = 63.00$, p (2-tailed) < .001	$U = 65.00$, p (2-tailed) < .05
Number of Type 4 conflict points	$H(3) = 29.30$, p (2-tailed) < .001	$U = 36.50$, p (2-tailed) < .001	$U = 77.50$, p (2-tailed) > .05
Number of Type 5 conflict points	$H(3) = 13.52$, p (2-tailed) < .05	$U = 133.00$, p (2-tailed) < .001	$U = 90.00$, p (2-tailed) > .05
Number of Type 6 conflict points	$H(3) = 4.40$, p (2-tailed) > .05	$U = 240.00$, p (2-tailed) > .05	$U = 96.00$, p (2-tailed) > .05
Number of Type 7 conflict points	$H(3) = 1.23$, p (2-tailed) > .05	$U = 279.00$, p (2-tailed) > .05	$U = 104.00$, p (2-tailed) > .05
Number of Type 8 conflict points	$H(3) = 2.71$, p (2-tailed) > .05	$U = 275.50$, p (2-tailed) > .05	$U = 104.00$, p (2-tailed) > .05
Total number of conflict points RWY-RWY	$H(3) = 10.73$, p (2-tailed) < .05	$U = 169.50$, p (2-tailed) < .001	$U = 110.50$, p (2-tailed) > .05
Total number of conflict points RWY-TWY	$H(3) = 26.62$, p (2-tailed) < .001	$U = 48.00$, p (2-tailed) < .001	$U = 71.00$, p (2-tailed) > .05
Total number of conflict points TWY-TWY	$H(3) = 25.51$, p (2-tailed) < .001	$U = 53.00$, p (2-tailed) < .001	$U = 76.50$, p (2-tailed) > .05
Total number of conflict points at the airport	$H(3) = 26.00$, p (2-tailed) < .001	$U = 51.00$, p (2-tailed) < .001	$U = 73.00$, p (2-tailed) > .05
Total number of segments in conflict with each other	$H(3) = 26.66$, p (2-tailed) < .001	$U = 49.50$, p (2-tailed) < .001	$U = 69.50$, p (2-tailed) > .05
Number of communication channels	$H(3) = 36.57$, p (2-tailed) < .001	$U = 8.00$, p (2-tailed) < .001	$U = 39.50$, p (2-tailed) < .05
Number of frequencies	$H(3) = 33.90$, p (2-tailed) < .001	$U = 7.00$, p (2-tailed) < .001	$U = 94.50$, p (2-tailed) > .05
Adequacy of equipment	$X^2 = 8.15$, p (2-tailed) < .05 [a]	$X^2 = .004$, p (2-tailed) > .05 [a]	$X^2 = .536$, p (2-tailed) > .05 [a]
Adequacy of visual aids	$X^2 = 16.07$, p (2-tailed) < .001 [a]	$X^2 = .111$, p (2-tailed) > .05 [a]	$X^2 = .905$, p (2-tailed) > .05 [a]

Complaints about lighting	X^2 = 4.14, p (2-tailed) > .05 [a]	X^2 = .647, p (2-tailed) > .05 [a]	X^2 = 1.36, p (2-tailed) > .05 [a]
Complaints about marking	X^2 = 1.89, p (2-tailed) > .05 [a]	X^2 = .126, p (2-tailed) > .05 [a]	X^2 = .914, p (2-tailed) > .05 [a]
Complaints about signage	X^2 = 7.04, p (2-tailed) > .05 [a]	X^2 = .051, p (2-tailed) > .05 [a]	X^2 = 2.12, p (2-tailed) > .05 [a]
Frequency of maintenance / construction work	X^2 = 32.18, p (2-tailed) < .001 [a]	X^2 = 7.26, p (2-tailed) > .05 [a]	X^2 = 12.40, p (2-tailed) < .05 [a]
Subcontractors working on the airfield	X^2 = 1.49, p (2-tailed) > .05 [a]	X^2 = .085, p (2-tailed) > .05 [a]	X^2 = .871, p (2-tailed) > .05 [a]
Requirement of clearances for all vehicle drivers	X^2 = 11.53, p (2-tailed) < .05 [a]	X^2 = .056, p (2-tailed) > .05 [a]	X^2 = 10.44, p (2-tailed) < .001 [a]
Vehicle equipment with radio communication	X^2 = 25.46, p (2-tailed) < .001 [a]	X^2 = 7.06, p (2-tailed) < .05 [a]	X^2 = 2.45, p (2-tailed) > .05 [a]
Number of runway condition checks	H (3) = 19.70, p (2-tailed) < .001 [a]	U = 90.00, p (2-tailed) < .001	U = 90.00, p (2-tailed) > .05
Use of runways as taxiways	X^2 = 13.50, p (2-tailed) < .05 [a]	X^2 = 5.61, p (2-tailed) > .05 [a]	X^2 = 6.50, p (2-tailed) < .05 [a]
Engagement in pro-active safety assessments	X^2 = 8.03, p (2-tailed) < .05 [a]	X^2 = 2.78, p (2-tailed) > .05 [a]	X^2 = 3.87, p (2-tailed) < .05 [a]
Adequacy of staffing level for airside operations	X^2 = 4.60, p (2-tailed) > .05 [a]	X^2 = 3.61, p (2-tailed) > .05 [a]	X^2 = .238, p (2-tailed) > .05 [a]
Adequacy of training for operational personnel	X^2 = 1.77, p (2-tailed) > .05 [a]	X^2 = 1.61, p (2-tailed) > .05 [a]	Variable is a constant
Adequacy of training for sub-contractors	X^2 = 6.32, p (2-tailed) > .05 [a]	X^2 = 3.64, p (2-tailed) > .05 [a]	X^2 = 1.04, p (2-tailed) > .05 [a]

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).
[a] The Pearson Chi-Square test assumptions are violated.

At the aggregated level, the majority of variables are heterogeneous and therefore not comparable between the countries. Some variables were found to be comparable. However, the statistical test assumptions for most of these tests are not fulfilled invalidating the results.

1.3 Associations Between Airport Characteristics and Incursion Rates

At the aggregated level the data was tested for associations between the number of incursions (per 100,000 movements) and the collected airport characteristics. The Pearson's and Spearman's Correlation Coefficients, Mann-Whitney U Test, Kruskal-Wallis Test, and the Pearson Chi-Square Test were applied as specified in Chapter 10 section 10.2.10.4. Table 3 contains the test statistics and significant test statistics ($p < .05$) are highlighted in grey.

Table 3: Associations between airport characteristics and the number of incursions (per 100,000 movements)

Variable	Complete data set
Average annual movements	r_S = -.670**, p (2-tailed) < .001
Altitude	r_S = -.135, p (2-tailed) > .05
Peak number of operations	r_S = -.627**, p (2-tailed) < .001
Number of runways	r_S = -.562**, p (2-tailed) < .001
Number of taxiway segments	r_S = -.567**, p (2-tailed) < .001
Number of Type 2 conflict points	r_S = -.496**, p (2-tailed) < .001
Number of Type 3 conflict points	r_S = -.541**, p (2-tailed) < .001
Number of Type 4 conflict points	r_S = -.585**, p (2-tailed) < .001
Number of Type 5 conflict points	r_S = -.354**, p (2-tailed) < .05
Number of Type 6 conflict points	r_S = -.218, p (2-tailed) > .05
Number of Type 7 conflict points	r_S = -.017, p (2-tailed) > .05
Number of Type 8 conflict points	r_S = .107, p (2-tailed) > .05
Total number of conflict points RWY-RWY	r_S = -.246, p (2-tailed) > .05
Total number of conflict points RWY-TWY	r_S = -.552**, p (2-tailed) < .001
Total number of conflict points TWY-TWY	r_S = -.535**, p (2-tailed) < .001
Total number of conflict points at the airport	r_S = -.551**, p (2-tailed) < .001
Total number of segments in conflict with each other	r_S = -.570**, p (2-tailed) < .001
Number of communication channels	r_S = -.675**, p (2-tailed) < .001
Number of frequencies	r_S = -.619**, p (2-tailed) < .001
Adequacy of equipment	U = 108.00, p (2-tailed) > .05
Adequacy of visual aids	U = 72.00, p (2-tailed) > .05
Complaints about lighting	$H(2)$ = .885, p (2-tailed) > .05
Complaints about marking	$H(2)$ = .235, p (2-tailed) > .05
Complaints about signage	$H(2)$ = .398, p (2-tailed) >.05

Frequency of maintenance / construction work	$H(4) = 26.90^*$, p (2-tailed) < .05
Subcontractors working on the airfield	$U = 138.00$, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	$H(1) = .136$, p (2-tailed) >.05
Vehicle equipment with radio communication	$H(2) = 7.99^*$ p (2-tailed) < .05
Number of runway condition checks	$r_S = -.370^*$, p (2-tailed) < .05
Use of runways as taxiways	$H(2) = 5.47$, p (2-tailed) > .05
Engagement in pro-active safety assessments	$U = 99.00^*$, p (2-tailed) < .05
Adequacy of staffing level for airside operations	$H(1) = 1.41$, p (2-tailed) > .05
Adequacy of training for operational personnel	$U = .000$, p (2-tailed) > .05
Adequacy of training for sub-contractors	$U = 72.00$, p (2-tailed) > .05

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

2 Analysis at the National Level

2.1 Normality Tests per Country

At a national level the continuous variables were tested for normality using the Shapiro-Wilk test for samples < 50. If the test statistic is significant ($p < .05$) then the data is not normally distributed. Table 4 contains the results. Normal distributed variables are indicated by means of a tick (✓) and highlighted in grey.

Table 4: Normality test per country

Variable	UK		U.S.		Norway	
	Complete data	Excluding outliers	Complete data	Excluding outliers	Complete data	Excluding outliers
Number of incursions (per 100,000 movements)	×	✓	×	✓	×	×
Number of excursions (per 100,000 movements)	×	×	n/a	n/a	×	×
Number of FOD (per 100,000 movements)	×	✓	n/a	n/a	×	×
Total number of occurrences (incursions + excursions + FOD)	×	✓	n/a	n/a	×	✓
Total number of occurrences (per 100,000 movements)	×	✓	n/a	n/a	×	✓
Average annual movements	×	×	✓	✓	×	×
Altitude	×	✓	×	×	×	×
Peak number of operations	×	✓	×	✓	×	×
Number of runways	×	×	✓	✓	×	Variable is constant
Number of taxiway segments	×	✓	✓	✓	×	×
Number of Type 2 conflict points	✓	✓	✓	✓	✓	×
Number of Type 3 conflict points	×	✓	✓	✓	×	×
Number of Type 4 conflict points	×	×	✓	✓	×	×
Number of Type 5 conflict points	×	×	×	×	×	Variable is constant
Number of Type 6 conflict points	×	Variable is constant	×	×	Variable is constant	Variable is constant
Number of Type 7 conflict points	×	Variable is constant	×	×	Variable is constant	Variable is constant
Number of Type 8 conflict points	×	Variable is constant	Variable is constant	Variable is constant	Variable is constant	Variable is constant
Total number of conflict points RWY-RWY	×	Variable is constant	×	×	×	Variable is constant
Total number of conflict points RWY-TWY	×	×	✓	✓	×	×
Total number of conflict points TWY-TWY	×	×	✓	✓	×	×

Total number of conflict points at the airport	×	×	✓	✓	×	×
Total number of segments in conflict with each other	×	×	✓	✓	×	×
Number of communication channels	×	×	✓	✓	×	×
Number of frequencies	×	✓	✓	✓	✓	✓

2.2 Summary of significant associations – excluding outliers

Table 5: Summary of significant associations – excluding outliers

Airport characteristic	Rate of occurrences							Severity*		Causal factors		
	Incursions			Excursions		FOD						
	U.S.	UK	NO	UK	NO	UK	NO	U.S.	UK	U.S.	UK	NO
Average annual movements	-	-	-	-	-	-	✔	✔	-	✔	-	✔
Altitude	-	-	-	✔	-	-	-	-	-	✔	-	✔
Peak number of operations	-	-	-	-	-	-	-	✔	-	✔	-	-
Number of runways	✔	-	-	-	-	-	-	✔	-	-	-	n/a
Number of taxiway segments	-	-	-	-	-	-	-	✔	-	✔	-	✔
Number of Type 2 conflict points	-	-	-	-	-	-	-	-	-	✔	-	✔
Number of Type 3 conflict points	-	-	-	-	-	-	-	✔	-	✔	-	✔
Number of Type 4 conflict points	-	-	-	-	-	-	-	✔	-	✔	-	-
Number of Type 5 conflict points	-	✔	-	-	-	-	-	✔	-	✔	✔	n/a
Number of Type 6 conflict points	-	-	-	-	-	-	-	-	-	✔	n/a	n/a
Total number of conflict points RWY-RWY	-	-	-	-	-	-	-	-	-	✔	n/a	n/a
Total number of conflict points RWY-TWY	-	-	-	-	-	-	-	✔	-	✔	-	✔
Total number of conflict points TWY-TWY	-	-	-	-	-	-	-	✔	-	✔	-	✔
Total number of conflict points at the airport	-	-	-	-	-	-	-	✔	-	✔	-	✔
Total number of segments in conflict with each other	-	-	-	-	-	-	-	✔	-	✔	-	✔
Number of communication channels	-	-	-	-	-	-	-	✔	-	✔	✔	-
Number of frequencies	-	-	-	-	-	-	-	✔	-	-	-	-
Adequacy of equipment		-	-	-	-	-	-	-[a]	-[a]	-[a]	✔	-[a]
Adequacy of visual aids	-	-	-	-	-	-	-	-[a]	n/a	-[a]	n/a	-[a]
Complaints about lighting	-	-	-	-	✔	-	-	✔	-	✔	-	✔[a]
Complaints about marking	-	-	-	-	-	-	-	-[a]	-	✔[a]	-	✔
Complaints about signage	-	-	-	-	-	-	-	-[a]	-	✔[a]	-	✔
Frequency of maintenance / construction work	-	-	-	-	-	-	-	n/a	n/a	n/a	n/a	✔[a]
Subcontractors working on the airfield	✔	-	-	-	-	-	✔	-	-[a]	✔	✔[a]	-
Requirement of clearances for all vehicle drivers	-	-	-	-	-	-	-	-	-	✔	✔	n/a
Vehicle equipment with radio communication	-	-	-	-	-	-	-	-	-	✔	✔	n/a
Number of runway condition checks	-	-	-	-	-	-	-	-	-	✔	-	✔
Use of runways as taxiways	-	-	-	-	-	-	-	✔	-	✔	✔[a]	✔
Engagement in pro-active safety assessments	-	-	-	-	-	-	-	-[a]	-[a]	✔	-[a]	✔

Adequacy of staffing level for airside operations	-	-	-	-	-	-	-	✔	-[a]	✔	-[a]	-
Adequacy of training for operational personnel	-	-	-	-	-	-	-	n/a	n/a	n/a	n/a	n/a
Adequacy of training for sub-contractors	-	-	-	-	-	-	-	-	n/a	✔	n/a	✔

*The associations between airport characteristics and runway incursion severity categories C and D were tested (1 October 2007–2009).
**The associations between airport characteristics and severity categories C and D were tested.
[a]: Tests assumptions are not fulfilled
n/a: The test statistic could not be computed, as one of the variables is a constant.

2.3 Test statistics

2.3.1 United Kingdom

At the national level. the data was tested for associations between the collected airport characteristics and i) the number of occurrences (per 100,000 movements), ii) the severity of occurrences, and iii) the causal factors. The appropriate statistical tests have been discussed in Chapter 10 section 10.2.10.4. Significant test statistics ($p < .05$) are highlighted in grey.

Table 6: Associations between airport characteristics and the number of incursions (per 100,000 movements) – UK

Variable	Complete data set	Excluding outliers
Average annual movements	$r_S = .174$, p (2-tailed) > .05	$r_S = .018$, p (2-tailed) > .05
Altitude	$r_S = .380$, p (2-tailed) > .05	$r = .017$ p (2-tailed) > .05
Peak number of operations	$r_S = .325$, p (2-tailed) > .05	$r = .052$, p (2-tailed) > .05
Number of runways	$r_S = .281$, p (2-tailed) > .05	$r_S = -.066$, p (2-tailed) > .05
Number of taxiway segments	$r_S = .108$, p (2-tailed) > .05	$r = -.132$, p (2-tailed) > .05
Number of Type 2 conflict points	$r_S = .239$, p (2-tailed) > .05	$r = .045$, p (2-tailed) > .05
Number of Type 3 conflict points	$r_S = .033$, p (2-tailed) > .05	$r = .043$, p (2-tailed) > .05
Number of Type 4 conflict points	$r_S = .211$, p (2-tailed) > .05	$r_S = -.157$, p (2-tailed) > .05
Number of Type 5 conflict points	$r_S = .290$, p (2-tailed) > .05	$r_S = .609$*, p (2-tailed) < .05
Number of Type 6 conflict points	$r_S = -.203$, p (2-tailed) > .05	Variable is a constant
Number of Type 7 conflict points	$r_S = .310$, p (2-tailed) > .05	Variable is a constant
Number of Type 8 conflict points	$r_S = .310$, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-RWY	$r_S = -.034$, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	$r_S = .038$, p (2-tailed) > .05	$r_S = -.102$, p (2-tailed) > .05
Total number of conflict points TWY-TWY	$r_S = .159$, p (2-tailed) > .05	$r_S = -.078$, p (2-tailed) > .05
Total number of conflict points at the airport	$r_S = .143$, p (2-tailed) > .05	$r_S = -.046$, p (2-tailed) > .05
Total number of segments in conflict with each other	$r_S = .156$, p (2-tailed) > .05	$r_S = -.091$, p (2-tailed) > .05
Number of communication channels	$r_S = .225$, p (2-tailed) > .05	$r_S = .317$, p (2-tailed) > .05
Number of frequencies	$r_S = .401$, p (2-tailed) > .05	$r = .141$, p (2-tailed) > .05
Adequacy of equipment	$U = 12.00$, p (2-tailed) > .05	$U = .000$, p (2-tailed) > .05
Adequacy of visual aids	Variable is a constant	Variable is a constant
Complaints about lighting	$H(1) = .156$, p (2-tailed) > .05	$H(1) = .889$, p (2-tailed) > .05
Complaints about marking	$H(1) = .491$, p (2-tailed) > .05	$H(1) = .000$, p (2-tailed) > .05

Complaints about signage	$H(1) = 2.67$, p (2-tailed) > .05	$H(1) = 2.26$, p (2-tailed) > .05
Frequency of maintenance / construction work	$H(1) = .145$, p (2-tailed) > .05	$H(1) = .260$, p (2-tailed) > .05
Subcontractors working on the airfield	$U = 4.00$, p (2-tailed) > .05	$U = 2.00$, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	$H(1) = 1.80$, p (2-tailed) > .05	$H(1) = .323$, p (2-tailed) > .05
Vehicle equipment with radio communication	$H(1) = .133$, p (2-tailed) > .05	$H(1) = .000$, p (2-tailed) > .05
Number of runway condition checks	$r_S = .551$*, p (2-tailed) < .05	$r_S = .509$, p (2-tailed) > .05
Use of runways as taxiways	$H(2) = .778$, p (2-tailed) > .05	$H(2) = .813$, p (2-tailed) > .05
Engagement in pro-active safety assessments	Variable is a constant	$U = 5.00$, p (2-tailed) > .05
Adequacy of staffing level for airside operations	$H(1) = .138$, p (2-tailed) > .05	$H(1) = .021$, p (2-tailed) > .05
Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	Variable is a constant	Variable is a constant

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 7: Associations between airport characteristics and the number of excursions (per 100,000 movements) – UK

Variable	**Complete data set**	**Excluding outliers**
Average annual movements	r_S = -.093, p (2-tailed) > .05	r_S = -.086, p (2-tailed) > .05
Altitude	r_S = .776**, p (2-tailed) < .001	r_S = .735*, p (2-tailed) < .05
Peak number of operations	r_S = -.175, p (2-tailed) > .05	r_S = .063, p (2-tailed) > .05
Number of runways	r_S = -.066, p (2-tailed) > .05	r_S = -.090, p (2-tailed) > .05
Number of taxiway segments	r_S = .041, p (2-tailed) > .05	r_S = .071, p (2-tailed) > .05
Number of Type 2 conflict points	r_S = .121, p (2-tailed) > .05	r_S = .188, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = -.055, p (2-tailed) > .05	r_S = -.055, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = .094, p (2-tailed) > .05	r_S = .094, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = -.138, p (2-tailed) > .05	r_S = .138, p (2-tailed) > .05
Number of Type 6 conflict points	r_S = .307, p (2-tailed) > .05	Variable is a constant
Number of Type 7 conflict points	r_S = -.035, p (2-tailed) > .05	Variable is a constant
Number of Type 8 conflict points	r_S = -.035, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-RWY	r_S = .104, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	r_S = -.325, p (2-tailed) > .05	r_S = -.340, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = .060, p (2-tailed) > .05	r_S = .095, p (2-tailed) > .05
Total number of conflict points at the airport	r_S = -.021, p (2-tailed) > .05	r_S = -.004, p (2-tailed) > .05
Total number of segments in conflict with each other	r_S = .022, p (2-tailed) > .05	r_S = .047, p (2-tailed) > .05
Number of communication channels	r_S = -.304, p (2-tailed) > .05	r_S = -.304, p (2-tailed) > .05
Number of frequencies	r_S = -.187, p (2-tailed) > .05	r_S = -.170, p (2-tailed) > .05
Adequacy of equipment	U = 11.50, p (2-tailed) > .05	U = 11.50, p (2-tailed) > .05
Adequacy of visual aids	Variable is a constant	Variable is a constant
Complaints about lighting	$H(1)$ = 1.93, p (2-tailed) > .05	$H(1)$ = 1.93, p (2-tailed) > .05
Complaints about marking	$H(1)$ = .000, p (2-tailed) > 05	$H(1)$ = .000, p (2-tailed) > .05
Complaints about signage	$H(1)$ = .006, p (2-tailed) >. 05	$H(1)$ = .006, p (2-tailed) > .05
Frequency of maintenance / construction work	$H(1)$ = -.301, p (2-tailed) > .05	$H(1)$ = -.301, p (2-tailed) > .05
Subcontractors working on the airfield	U = 1.50, p (2-tailed) > .05	U = 1.50, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	$H(1)$ = .338, p (2-tailed) > .05	$H(1)$ = .338, p (2-tailed) >. 05
Vehicle equipment with radio communication	$H(1)$ = 1.03, p (2-tailed) > .05	$H(1)$ = 1.03, p (2-tailed) > .05
Number of runway condition checks	r_S = .374, p (2-tailed) > .05	r_S = -.374, p (2-tailed) > .05
Use of runways as taxiways	$H(2)$ = 3.65, p (2-tailed) > .05	$H(2)$ = 3.65, p (2-tailed) > .05
Engagement in pro-active safety assessments	U = 1.50, p (2-tailed) > .05	U = 1.50, p (2-tailed) > .05
Adequacy of staffing level for airside operations	$H(1)$ = 1.57, p (2-tailed) > .05	$H(1)$ = 1.57, p (2-tailed) > .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	Variable is a constant	Variable is a constant

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 8: Associations between airport characteristics and the number of FOD (per 100,000 movements) – UK

Variable	**Complete data set**	**Excluding outliers**
Average annual movements	r_S = .178, p (2-tailed) > .05	r_S = .256, p (2-tailed) > .05
Altitude	r_S = -.282, p (2-tailed) > .05	r = -.303, p (2-tailed) > .05
Peak number of operations	r_S = .115, p (2-tailed) > .05	r = .280, p (2-tailed) > .05
Number of runways	r_S = -.032, p (2-tailed) > .05	r_S = .309, p (2-tailed) > .05
Number of taxiway segments	r_S = .256, p (2-tailed) > .05	r = .466, p (2-tailed) > .05
Number of Type 2 conflict points	r_S = .287, p (2-tailed) > .05	r = .050, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = .163, p (2-tailed) > .05	r = .197, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = .171, p (2-tailed) > .05	r_S = .119, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = .173, p (2-tailed) > .05	r_S = -.267, p (2-tailed) > .05
Number of Type 6 conflict points	r_S = -.282, p (2-tailed) > .05	Variable is a constant
Number of Type 7 conflict points	r_S = -.104, p (2-tailed) > .05	Variable is a constant
Number of Type 8 conflict points	r_S = -.104, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-RWY	r_S = -.348, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	r_S = .274, p (2-tailed) > .05	r_S = .428, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = .217, p (2-tailed) > .05	r_S = .180, p (2-tailed) > .05
Total number of conflict points at the airport	r_S = .212, p (2-tailed) > .05	r_S = .175, p (2-tailed) > .05
Total number of segments in conflict with each other	r_S = .213, p (2-tailed) > .05	r_S = .182, p (2-tailed) > .05
Number of communication channels	r_S = .372, p (2-tailed) > .05	r_S = .301, p (2-tailed) > .05
Number of frequencies	r_S = .307, p (2-tailed) > .05	r = .558, p (2-tailed) > .05
Adequacy of equipment	U = 10.50, p (2-tailed) > .05	U = 10.50, p (2-tailed) > .05
Adequacy of visual aids	Variable is a constant	Variable is a constant
Complaints about lighting	H(1) = 3.25, p (2-tailed) > .05	H(1) = 3.06, p (2-tailed) > .05
Complaints about marking	H(1) = .223, p (2-tailed) > .05	H(1) = .066, p (2-tailed) > .05
Complaints about signage	H(1) = .2.73, p (2-tailed) > .05	H(1) = 1.00, p (2-tailed) > .05
Frequency of maintenance / construction work	H(1) = .150, p (2-tailed) > .05	H(1) = .204, p (2-tailed) > .05
Subcontractors working on the airfield	U = 4.00, p (2-tailed) > .05	U = 3.00, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	H(1) = .204, p (2-tailed) > .05	H(1) = .000, p (2-tailed) > .05
Vehicle equipment with radio communication	H(1) = .136, p (2-tailed) >.05	H(1) = .361, p (2-tailed) > .05
Number of runway condition checks	r_S = .331, p (2-tailed) > .05	r_S = .470, p (2-tailed) > .05
Use of runways as taxiways	H(2) = .511, p (2-tailed) > .05	H(2) = 1.25, p (2-tailed) > .05
Engagement in pro-active safety assessments	U = 6.00, p (2-tailed) > .05	U = 5.00, p (2-tailed) > .05
Adequacy of staffing level for airside operations	H(1) = .016, p (2-tailed) > .05	H(1) = .073, p (2-tailed) > .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	Variable is a constant	Variable is a constant

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 9: Associations between airport characteristics and the number of total occurrences (per 100,000 movements) – UK

Variable	**Complete data set**	**Excluding outliers**
Average annual movements	r_S = .191, p (2-tailed) > .05	r_S = .018, p (2-tailed) > .05
Altitude	r_S = .477, p (2-tailed) > .05	r = .214, p (2-tailed) > .05
Peak number of operations	r_S = .256, p (2-tailed) > .05	r = .087, p (2-tailed) > .05
Number of runways	r_S = .200, p (2-tailed) > .05	r_S = .258, p (2-tailed) > .05
Number of taxiway segments	r_S = .205, p (2-tailed) > .05	r = -.050, p (2-tailed) > .05
Number of Type 2 conflict points	r_S = .350, p (2-tailed) > .05	r = .154, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = .064, p (2-tailed) > .05	r = .023, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = .262, p (2-tailed) > .05	r_S = -.065, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = .241, p (2-tailed) > .05	r_S = .418, p (2-tailed) > .05
Number of Type 6 conflict points	r_S = -.101, p (2-tailed) > .05	Variable is a constant
Number of Type 7 conflict points	r_S = .241, p (2-tailed) > .05	Variable is a constant
Number of Type 8 conflict points	r_S = .241, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-RWY	r_S = -.103, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	r_S = .011, p (2-tailed) > .05	r_S = -.195, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = .236, p (2-tailed) > .05	r_S = .046, p (2-tailed) > .05
Total number of conflict points at the airport	r_S = .198, p (2-tailed) > .05	r_S = .032, p (2-tailed) > .05
Total number of segments in conflict with each other	r_S = .222, p (2-tailed) > .05	r_S = -.009, p (2-tailed) > .05
Number of communication channels	r_S = .237, p (2-tailed) > .05	r_S = .294, p (2-tailed) > .05
Number of frequencies	r_S = .383, p (2-tailed) > .05	r = .157, p (2-tailed) > .05
Adequacy of equipment	U = 11.00, p (2-tailed) > .05	U = .000, p (2-tailed) > .05
Adequacy of visual aids	Variable is a constant	Variable is a constant
Complaints about lighting	$H(1)$ = .000, p (2-tailed) > .05	$H(1)$ = .222, p (2-tailed) > .05
Complaints about marking	$H(1)$ = .152, p (2-tailed) > .05	$H(1)$ = .046, p (2-tailed) > .05
Complaints about signage	$H(1)$ = 5.10*, p (2-tailed) < .05	$H(1)$ = 4.62*, p (2-tailed) < .05
Frequency of maintenance / construction work	$H(1)$ = .087, p (2-tailed) > .05	$H(1)$ = .186, p (2-tailed) > .05
Subcontractors working on the airfield	U = 5.00, p (2-tailed) > .05	U = 3.00, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	$H(1)$ = .690, p (2-tailed) > .05	$H(1)$ = .007, p (2-tailed) > .05
Vehicle equipment with radio communication	$H(1)$ = .300, p (2-tailed) >.05	$H(1)$ = .046, p (2-tailed) > .05
Number of runway condition checks	r_S = .438, p (2-tailed) > .05	r_S = .318, p (2-tailed) > .05
Use of runways as taxiways	$H(2)$ = .221, p (2-tailed) > .05	$H(2)$ = .063, p (2-tailed) > .05
Engagement in pro-active safety assessments	U = 4.00, p (2-tailed) > .05	U = 4.00, p (2-tailed) > .05
Adequacy of staffing level for airside operations	$H(1)$ = .385, p (2-tailed) > .05	$H(1)$ = .189, p (2-tailed) > .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	Variable is a constant	Variable is a constant

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 10: Associations between airport characteristics and causal factors – UK

Variable	Complete data set	Excluding outliers
Average annual movements	$H(2) = 6.239$*, p (2-tailed) < .05	$H(2) = 1.045$, p (2-tailed) > .05
Altitude	$H(2) = 11.708$*, p (2-tailed) < .05	$H(2) = 3.759$, p (2-tailed) > .05
Peak number of operations	$H(2) = 6.694$*, p (2-tailed) < .05	$H(2) = 5.777$, p (2-tailed) > .05
Number of runways	$H(2) = 10.635$*, p (2-tailed) < .05	$H(2) = 5.887$, p (2-tailed) > .05
Number of taxiway segments	$H(2) = 5.119$, p (2-tailed) > .05	$H(2) = 1.167$, p (2-tailed) > .05
Number of Type 2 conflict points	$H(2) = 7.827$*, p (2-tailed) < .05	$H(2) = .117$, p (2-tailed) > .05
Number of Type 3 conflict points	$H(2) = 6.141$*, p (2-tailed) < .05	$H(2) = .369$, p (2-tailed) > .05
Number of Type 4 conflict points	$H(2) = 4.444$, p (2-tailed) > .05	$H(2) = 5.878$, p (2-tailed) > .05
Number of Type 5 conflict points	$H(2) = 3.976$, p (2-tailed) > .05	$H(2) = 9.759$*, p (2-tailed) < .05
Number of Type 6 conflict points	$H(2) = 5.99$*, p (2-tailed) < .05	Variable is a constant
Number of Type 7 conflict points	$H(2) = 9.113$*, p (2-tailed) < .05	Variable is a constant
Number of Type 8 conflict points	$H(2) = 9.113$*, p (2-tailed) < .05	Variable is a constant
Total number of conflict points RWY-RWY	$H(2) = 11.598$*, p (2-tailed) < .05	Variable is a constant
Total number of conflict points RWY-TWY	$H(2) = 6.682$*, p (2-tailed) < .05	$H(2) = .744$, p (2-tailed) > .05
Total number of conflict points TWY-TWY	$H(2) = 3.920$, p (2-tailed) > .05	$H(2) = 2.077$, p (2-tailed) > .05
Total number of conflict points at the airport	$H(2) = 5.977$, p (2-tailed) > .05	$H(2) = .182$, p (2-tailed) > .05
Total number of segments in conflict with each other	$H(2) = 5.380$, p (2-tailed) > .05	$H(2) = 1.292$, p (2-tailed) > .05
Number of communication channels	$H(2) = 8.789$*, p (2-tailed) < .05	$H(2) = 8.789$*, p (2-tailed) < .05
Number of frequencies	$H(2) = 3.844$, p (2-tailed) > .05	$H(2) = 1.956$ p (2-tailed) > .05
Adequacy of equipment	$X^2 = 12.757$*, p (2-tailed) < .05	$X^2 = 12.757$*, p (2-tailed) < .05
Adequacy of visual aids	Variable is a constant	Variable is a constant
Complaints about lighting	$X^2 = 6.153$, p (2-tailed) > .05	$X^2 = 6.153$, p (2-tailed) > .05
Complaints about marking	$X^2 = 5.814$, p (2-tailed) > .05	$X^2 = 5.814$, p (2-tailed) > .05
Complaints about signage	$X^2 = .623$, p (2-tailed) > .05	$X^2 = .623$, p (2-tailed) > .05
Frequency of maintenance / construction work	Variable is a constant	Variable is a constant
Subcontractors working on the airfield	$X^2 = 37.654$**, p (2-tailed) < .001 [a]	$X^2 = 37.654$**, p (2-tailed) < .001 [a]
Requirement of clearances for all vehicle drivers	$X^2 = 15.288$**, p (2-tailed) < .001	$X^2 = 15.288$**, p (2-tailed) < .001
Vehicle equipment with radio communication	$X^2 = 7.986$*, p (2-tailed) < .05	$X^2 = 7.986$*, p (2-tailed) < .05
Number of runway condition checks	$H(2) = 2.232$, p (2-tailed) > .05	$H(2) = 3.232$, p (2-tailed) > .05
Use of runways as taxiways	$X^2 = 14.913$*, p (2-tailed) < .05 [a]	$X^2 = 14.913$*, p (2-tailed) < .05 [a]
Engagement in pro-active safety assessments	$X^2 = 2.990$, p (2-tailed) > .05 [a]	$X^2 = 2.990$, p (2-tailed) > .05 [a]
Adequacy of staffing level for airside operations	$X^2 = 2.990$, p (2-tailed) > .05 [a]	$X^2 = 2.990$, p (2-tailed) > .05 [a]

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	Variable is a constant	Variable is a constant

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).
[a] The Pearson Chi-Square test assumptions are violated.

2.3.2 United States

Table 11: Associations between airport characteristics and the number of incursions – U.S.

Variable	Complete data set	Excluding outliers
Average annual movements	r_S = .019, p (2-tailed) > .05	r = .149, p (2-tailed) > .05
Altitude	r_S = -.069, p (2-tailed) > .05	r_S = -.105, p (2-tailed) > .05
Peak number of operations	r_S = -.005, p (2-tailed) > .05	r = .086, p (2-tailed) > .05
Number of runways	r_S = .206, p (2-tailed) > .05	r = .527*, p (2-tailed) < .05
Number of taxiway segments	r_S = .019, p (2-tailed) > .05	r = .111, p (2-tailed) > .05
Number of Type 2 conflict points	r_S = .522*, p (2-tailed) < .05	r = .396, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = .093, p (2-tailed) > .05	r = .134, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = -.026, p (2-tailed) > .05	r = .189, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = -.003, p (2-tailed) > .05	r_S = .078, p (2-tailed) > .05
Number of Type 6 conflict points	r_S = .143, p (2-tailed) > .05	r_S = .158, p (2-tailed) > .05
Number of Type 7 conflict points	r_S = .086, p (2-tailed) > .05	r_S = .117, p (2-tailed) > .05
Number of Type 8 conflict points	Variable is a constant	Variable is a constant
Total number of conflict points RWY-RWY	r_S = .552*, p (2-tailed) < .05	r_S = .471, p (2-tailed) > .05
Total number of conflict points RWY-TWY	r_S = .142, p (2-tailed) > .05	r = .307, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = .063, p (2-tailed) > .05	r = .053, p (2-tailed) > .05
Total number of conflict points at the airport	r_S = .063, p (2-tailed) > .05	r = .147, p (2-tailed) > .05
Total number of segments in conflict with each other	r_S = .017, p (2-tailed) > .05	r = .158, p (2-tailed) > .05
Number of communication channels	r_S = .284, p (2-tailed) > .05	r = .465, p (2-tailed) > .05
Number of frequencies	r_S = .185, p (2-tailed) > .05	r = .306, p (2-tailed) > .05
Adequacy of equipment	U = 3.00, p (2-tailed) > .05	U = 3.00, p (2-tailed) > .05
Adequacy of visual aids	U = 4.00, p (2-tailed) > .05	U = 4.00, p (2-tailed) > .05
Complaints about lighting	H(1) = 2.83, p (2-tailed) > .05	H(1) = .494, p (2-tailed) > .05
Complaints about marking	H(2) = 1.76, p (2-tailed) > .05	H(2) = 1.76, p (2-tailed) > .05
Complaints about signage	H(2) = 2.41, p (2-tailed) > .05	H(2) = 2.82, p (2-tailed) > .05
Frequency of maintenance / construction work	H(1) = -.325, p (2-tailed) > .05	H(1) = -.334, p (2-tailed) > .05
Subcontractors working on the airfield	U = 2.00*, p (2-tailed) < .05	U = 2.00*, p (2-tailed) < .05
Requirement of clearances for all vehicle drivers	H(1) = 1.04, p (2-tailed) > .05	H(1) = 1.77, p (2-tailed) > .05
Vehicle equipment with radio communication	H(1) = 0.865, p (2-tailed) > .05	H(1) = 2.54, p (2-tailed) > .05
Number of runway condition checks	r_S = -.024, p (2-tailed) > .05	r_S = -.144, p (2-tailed) > 0.5

Use of runways as taxiways	$H(2) = .916$, p (2-tailed) > .05	$H(2) = .281$, p (2-tailed) >.05
Engagement in pro-active safety assessments	$U = 2.00$, p (2-tailed) > .05	$U = 1.00$, p (2-tailed) > .05
Adequacy of staffing level for airside operations	$H(1) = .695$, p (2-tailed) >.05	$H(1) = 2.49$, p (2-tailed) > .05
Adequacy of training for operational personnel	$U = .00$, p (2-tailed) > .05	$U = .00$, p (2-tailed) > .05
Adequacy of training for sub-contractors	$U = 12.00$, p (2-tailed) > .05	$U = 12.00$, p (2-tailed) > .05

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).
The analysis uses the data available from 2005-2009.

Table 12: Associations between airport characteristics and the severity of runway incursions – U.S.

Variable	Complete data set (only Cat C, D, excl. A, B)	Excluding outliers (only Cat C, D, excl. A, B)
Average annual movements	U = 7723.50**, p (2-tailed) < .001	U = 7723.50**, p (2-tailed) < .001
Altitude	U = 8871.50, p (2-tailed) > .05	U = 8868.50, p (2-tailed) > .05
Peak number of operations	U = 6779.50**, p (2-tailed) < .001	U = 5711.00**, p (2-tailed) < .001
Number of runways	U = 6584.50**, p (2-tailed) < .001	U = 4343.50**, p (2-tailed) < .001
Number of taxiway segments	U = 7513.50**, p (2-tailed) < .001	U = 7513.50**, p (2-tailed) < .001
Number of Type 2 conflict points	U = 9147.00, p (2-tailed) > .05	U = 9147.00, p (2-tailed) > .05
Number of Type 3 conflict points	U = 7761.50**, p (2-tailed) < .001	U = 7761.50**, p (2-tailed) < .001
Number of Type 4 conflict points	U = 7111.00**, p (2-tailed) < .001	U = 6043.00**, p (2-tailed) < .001
Number of Type 5 conflict points	U = 8033.00*, p (2-tailed) < .05	U = 6965.00*, p (2-tailed) < .05
Number of Type 6 conflict points	U = 8730.00*, p (2-tailed) < .05	U = 7662.00, p (2-tailed) > .05
Number of Type 7 conflict points	U = 9186.00*, p (2-tailed) < .05	U = 9186.00*, p (2-tailed) < .05
Number of Type 8 conflict points	U = 10080.00, p (2-tailed) > .05	U = 10080.00, p (2-tailed) > .05
Total number of conflict points RWY-RWY	U = 9607.00, p (2-tailed) > .05	U = 8123.00, p (2-tailed) > .05
Total number of conflict points RWY-TWY	U = 6799.50**, p (2-tailed) < .001	U = 5731.50**, p (2-tailed) < .001
Total number of conflict points TWY-TWY	U = 7527.50**, p (2-tailed) < .001	U = 7527.50**, p (2-tailed) < .001
Total number of conflict points at the airport	U = 7448.50**, p (2-tailed) < .001	U = 7448.50**, p (2-tailed) < .001
Total number of segments in conflict with each other	U = 7435.50**, p (2-tailed) < .001	U = 7435.50**, p (2-tailed) < .001
Number of communication channels	U = 8548.50*, p (2-tailed) < .05	U = 8548.50*, p (2-tailed) < .05
Number of frequencies	U = 8287.00*, p (2-tailed) < .05	U = 8287.00*, p (2-tailed) < .05
Adequacy of equipment	X^2 = .366, p (2-tailed) > .05 [a]	X^2 = .366, p (2-tailed) > .05 [a]
Adequacy of visual aids	X^2 = .366, p (2-tailed) > .05 [a]	X^2 = .366, p (2-tailed) > .05 [a]
Complaints about lighting	X^2 = 6.09* p (2-tailed) < .05	X^2 = 6.09* p (2-tailed) < .05
Complaints about marking	X^2 = 1.17 p (2-tailed) > .05 [a]	X^2 = 1.17 p (2-tailed) > .05 [a]
Complaints about signage	X^2 = 1.42, p (2-tailed) > .05 [a]	X^2 = 1.42, p (2-tailed) > .05 [a]
Frequency of maintenance / construction work	Variable is a constant	Variable is a constant
Subcontractors working on the airfield	X^2 = 3.31, p (2-tailed) > .05	X^2 = 3.31, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	X^2 = 2.45, p (2-tailed) > .05	X^2 = 2.45, p (2-tailed) > .05
Vehicle equipment with radio communication	X^2 = .185, p (2-tailed) > .05	X^2 = .185, p (2-tailed) > .05
Number of runway condition checks	U = 68328.50, p (2-tailed) < .05	U = 6117.50, p (2-tailed) > .05
Use of runways as taxiways	X^2 = 8.14*, p (2-tailed) < .05	X^2 = 8.14*, p (2-tailed) < .05
Engagement in pro-active safety assessments	X^2 = .001, p (2-tailed) > .05 [a]	X^2 = .001, p (2-tailed) > .05 [a]
Adequacy of staffing level for airside operations	X^2 = 6.54*, p (2-tailed) < .05	X^2 = 6.54*, p (2-tailed) < .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	X^2 = .779, p (2-tailed) > .05	X^2 = .779, p (2-tailed) > .05

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).
[a] The Pearson Chi-Square test assumptions are violated.
The analysis uses the data available from 1 October 2007-2009.

Table 13: Associations between airport characteristics and causal factors – U.S.

Variable	Complete data set	Excluding outliers
Average annual movements	$H(2) = 26.14^{**}$, p (2-tailed) < .001	$H(2) = 26.14^{**}$, p (2-tailed) < .001
Altitude	$H(2) = 16.85^{**}$, p (2-tailed) < .001	$H(2) = 20.61^{**}$, p (2-tailed) < .001
Peak number of operations	$H(2) = 48.52^{**}$, p (2-tailed) < .001	$H(2) = 36.10^{**}$, p (2-tailed) < .001
Number of runways	$H(2) = 13.12^{**}$, p (2-tailed) < .001	$H(2) = 5.21$, p (2-tailed) > .05
Number of taxiway segments	$H(2) = 31.36^{**}$, p (2-tailed) < .001	$H(2) = 31.56^{**}$, p (2-tailed) < .001
Number of Type 2 conflict points	$H(2) = 10.24^{*}$, p (2-tailed) < .05	$H(2) = 10.24^{*}$, p (2-tailed) < .05
Number of Type 3 conflict points	$H(2) = 25.41^{**}$, p (2-tailed) < .001	$H(2) = 25.41^{**}$, p (2-tailed) < .001
Number of Type 4 conflict points	$H(2) = 22.29^{**}$, p (2-tailed) < .001	$H(2) = 11.75^{**}$, p (2-tailed) < .05
Number of Type 5 conflict points	$H(2) = 43.01^{**}$, p (2-tailed) < .001	$H(2) = 31.05^{**}$, p (2-tailed) < .001
Number of Type 6 conflict points	$H(2) = 53.40^{**}$, p (2-tailed) < .001	$H(2) = 53.40^{**}$, p (2-tailed) < .001
Number of Type 7 conflict points	$H(2) = 15.85^{**}$, p (2-tailed) < .001	$H(2) = 15.85^{**}$, p (2-tailed) < .001
Number of Type 8 conflict points	$H(2) = .000$, p (2-tailed) > .05	$H(2) = .000$, p (2-tailed) > .05
Total number of conflict points RWY-RWY	$H(2) = 3.74$, p (2-tailed) > .05	$H(2) = 10.03^{*}$, p (2-tailed) < .05
Total number of conflict points RWY-TWY	$H(2) = 15.47^{**}$, p (2-tailed) < .001	$H(2) = 6.74^{*}$, p (2-tailed) < .05
Total number of conflict points TWY-TWY	$H(2) = 30.71^{**}$, p (2-tailed) < .001	$H(2) = 30.71^{**}$, p (2-tailed) < .001
Total number of conflict points at the airport	$H(2) = 30.20^{**}$, p (2-tailed) < .001	$H(2) = 30.20^{**}$, p (2-tailed) < .001
Total number of segments in conflict with each other	$H(2) = 31.72^{**}$, p (2-tailed) < .001	$H(2) = 31.72^{**}$, p (2-tailed) < .001
Number of communication channels	$H(2) = 7.12^{*}$, p (2-tailed) < .05	$H(2) = 7.12^{*}$, p (2-tailed) < .05
Number of frequencies	$H(2) = 5.23$, p (2-tailed) > .05	$H(2) = 5.23$, p (2-tailed) > .05
Adequacy of equipment	$X^2 = 1.39$, p (2-tailed) > .05 [a]	$X^2 = 1.39$, p (2-tailed) > .05 [a]
Adequacy of visual aids	$X^2 = 1.39$, p (2-tailed) > .05 [a]	$X^2 = 1.39$, p (2-tailed) > .05 [a]
Complaints about lighting	$X^2 = 27.60^{**}$, p (2-tailed) < .001	$X^2 = 27.60^{**}$, p (2-tailed) < .001
Complaints about marking	$X^2 = 14.51^{*}$, p (2-tailed) < .05 [a]	$X^2 = 14.51^{*}$, p (2-tailed) < .05 [a]
Complaints about signage	$X^2 = 9.59^{*}$, p (2-tailed) < .05 [a]	$X^2 = 9.59^{*}$, p (2-tailed) < .05 [a]
Frequency of maintenance / construction work	Variable is a constant	Variable is a constant
Subcontractors working on the airfield	$X^2 = 8.80^{*}$, p (2-tailed) < .05	$X^2 = 8.80^{*}$, p (2-tailed) < .05
Requirement of clearances for all vehicle drivers	$X^2 = 9.64^{*}$, p (2-tailed) < .05	$X^2 = 9.64^{*}$, p (2-tailed) < .05
Vehicle equipment with radio communication	$X^2 = 11.19^{*}$, p (2-tailed) < .05	$X^2 = 11.19^{*}$, p (2-tailed) < .05
Number of runway condition checks	$H(2) = 35.14^{**}$, p (2-tailed) < .001	$H(2) = 17.19^{**}$, p (2-tailed) < .001
Use of runways as taxiways	$X^2 = 75.40^{*}$, p (2-tailed) < .001	$X^2 = 75.40^{*}$, p (2-tailed) < .001
Engagement in pro-active safety assessments	$X^2 = 7.56^{*}$, p (2-tailed) < .05	$X^2 = 7.56^{*}$, p (2-tailed) < .05
Adequacy of staffing level for airside operations	$X^2 = 6.59^{*}$, p (2-tailed) < .05	$X^2 = 6.59^{*}$, p (2-tailed) < .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	X^2 = 12.46*, p (2-tailed) < .05	X^2 = 12.46*, p (2-tailed) < .05

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).
[a] The Pearson Chi-Square test assumptions are violated.
The analysis uses the data available from 2005-2009.

2.3.3 Norway

Table 14: Associations between airport characteristics and the number of incursions (per 100,000 movements) – Norway

Variable	Complete data set	Excluding outliers
Average annual movements	r_S = -.659*, p (2-tailed) < .05	r_S = -.527, p (2-tailed) > .05
Altitude	r_S = .154, p (2-tailed) > .05	r_S = -.196, p (2-tailed) > .05
Peak number of operations	r_S = -.287, p (2-tailed) > .05	r_S = -.452, p (2-tailed) > .05
Number of runways	r_S = -.087, p (2-tailed) > .05	Variable is a constant
Number of taxiway segments	r_S = -.355, p (2-tailed) > .05	r_S = -.456, p (2-tailed) > .05
Number of Type 2 conflict points	r_S = -.150, p (2-tailed) > .05	r_S = -.258, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = -.403, p (2-tailed) > .05	r_S = -.440, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = -.191, p (2-tailed) > .05	r_S = -.383, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = .253, p (2-tailed) > .05	Variable is a constant
Number of Type 6 conflict points	Variable is a constant	Variable is a constant
Number of Type 7 conflict points	Variable is a constant	Variable is a constant
Number of Type 8 conflict points	Variable is a constant	Variable is a constant
Total number of conflict points RWY-RWY	r_S = .084, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	r_S = -.331, p (2-tailed) > .05	r_S = -.347, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = -.296, p (2-tailed) > .05	r_S = -.435, p (2-tailed) > .05
Total number of conflict points at the airport	r_S = -.383, p (2-tailed) > .05	r_S = -.431, p (2-tailed) > .05
Total number of segments in conflict with each other	r_S = -.369, p (2-tailed) > .05	r_S = -.410, p (2-tailed) > .05
Number of communication channels	r_S = -.322, p (2-tailed) > .05	r_S = -.385, p (2-tailed) > .05
Number of frequencies	r_S = -.292, p (2-tailed) > .05	r_S = -.478, p (2-tailed) > .05
Adequacy of equipment	U = 2.00, p (2-tailed) > .05	U = 2.00, p (2-tailed) > .05
Adequacy of visual aids	U = 2.00, p (2-tailed) > .05	U = 2.00, p (2-tailed) > .05
Complaints about lighting	H(2) = .819, p (2-tailed) > .05	H(2) = 1.33, p (2-tailed) > .05
Complaints about marking	H(2) = .588, p (2-tailed) > .05	H(2) = 3.02, p (2-tailed) > .05
Complaints about signage	H(2) = 3.35, p (2-tailed) > .05	H(2) = 3.02, p (2-tailed) > .05
Frequency of maintenance / construction work	H(4) = -.218, p (2-tailed) > .05	H(4) = .175, p (2-tailed) > .05
Subcontractors working on the airfield	U = 18.00, p (2-tailed) > .05	U = 15.00, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	Variable is a constant	Variable is a constant
Vehicle equipment with radio communication	Variable is a constant	Variable is a constant
Number of runway condition checks	r_S = .092, p (2-tailed) > .05	r_S = -.100, p (2-tailed) > .05
Use of runways as taxiways	H(2) = .201, p (2-tailed) > .05	H(2) = 3.77, p (2-tailed) > .05

Engagement in pro-active safety assessments	U = 16.00, p (2-tailed) > .05	U = 16.00, p (2-tailed) > .05
Adequacy of staffing level for airside operations	H(1) = .908, p (2-tailed) > .05	H(1) = .015, p (2-tailed) > .05
Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	U = .000, p (2-tailed) > .05	Variable is a constant

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 15: Associations between airport characteristics and the number of excursions (per 100,000 movements) – Norway

Variable	**Complete data set**	**Excluding outliers**
Average annual movements	r_S = .173, p (2-tailed) > .05	r_S = -.024, p (2-tailed) > .05
Altitude	r_S = .060 p (2-tailed) > .05	r_S = -.231 p (2-tailed) > .05
Peak number of operations	r_S = .492, p (2-tailed) > .05	r_S = .312, p (2-tailed) > .05
Number of runways	r_S = .127, p (2-tailed) > .05	Variable is a constant
Number of taxiway segments	r_S = .282, p (2-tailed) > .05	r_S = .109, p (2-tailed) > .05
Number of Type 2 conflict points	r_S = -.004, p (2-tailed) > .05	r_S = -.004, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = .274, p (2-tailed) > .05	r_S = .098, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = .219, p (2-tailed) > .05	r_S = .219, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = -.228, p (2-tailed) > .05	Variable is a constant
Number of Type 6 conflict points	Variable is a constant	Variable is a constant
Number of Type 7 conflict points	Variable is a constant	Variable is a constant
Number of Type 8 conflict points	Variable is a constant	Variable is a constant
Total number of conflict points RWY-RWY	r_S = -.123, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	r_S = .331, p (2-tailed) > .05	r_S = .331, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = .136, p (2-tailed) > .05	r_S = .136, p (2-tailed) > .05
Total number of conflict points at the airport	r_S = .248, p (2-tailed) > .05	r_S = .248, p (2-tailed) > .05
Total number of segments in conflict with each other	r_S = .284, p (2-tailed) > .05	r_S = .284, p (2-tailed) > .05
Number of communication channels	r_S = .459, p (2-tailed) > .05	r_S = .426, p (2-tailed) > .05
Number of frequencies	r_S = -.423, p (2-tailed) > .05	r_S = .210, p (2-tailed) > .05
Adequacy of equipment	U = 6.00, p (2-tailed) > .05	U = 6.00, p (2-tailed) > .05
Adequacy of visual aids	U = 6.00, p (2-tailed) > .05	U = 6.00, p (2-tailed) > .05
Complaints about lighting	$H(2)$ = 9.36*, p (2-tailed) < .05	$H(2)$ = 9.36*, p (2-tailed) < .05
Complaints about marking	$H(2)$ = 3.52, p (2-tailed) > 05	$H(2)$ = 3.52, p (2-tailed) > 05
Complaints about signage	$H(2)$ = 1.20, p (2-tailed) >. 05	$H(2)$ = 1.20, p (2-tailed) >. 05
Frequency of maintenance / construction work	$H(4)$ = .048, p (2-tailed) > .05	$H(4)$ = .048, p (2-tailed) > .05
Subcontractors working on the airfield	U = 15.00, p (2-tailed) > .05	U = 15.00, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	Variable is a constant	Variable is a constant
Vehicle equipment with radio communication	Variable is a constant	Variable is a constant
Number of runway condition checks	r_S = .387, p (2-tailed) > .05	r_S = .387, p (2-tailed) > .05
Use of runways as taxiways	$H(2)$ = 4.40, p (2-tailed) > .05	$H(2)$ = 4.40, p (2-tailed) > .05
Engagement in pro-active safety assessments	U = 30.00, p (2-tailed) > .05	U = 30.00, p (2-tailed) > .05
Adequacy of staffing level for airside operations	$H(1)$ = .488, p (2-tailed) > .05	$H(1)$ = .488, p (2-tailed) > .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	$U = 6.00$, p (2-tailed) > .05	$U = 6.00$, p (2-tailed) > .05

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 16: Associations between airport characteristics and the number of FOD (per 100,000 movements) – Norway

Variable	Complete data set	Excluding outliers
Average annual movements	r_S = .457, p (2-tailed) > .05	r_S = .538*, p (2-tailed) < .05
Altitude	r_S = -.135 p (2-tailed) > .05	r_S = .193 p (2-tailed) > .05
Peak number of operations	r_S = .021, p (2-tailed) > .05	r_S = .097, p (2-tailed) > .05
Number of runways	r_S = -.264, p (2-tailed) > .05	Variable is a constant
Number of taxiway segments	r_S = -.186, p (2-tailed) > .05	r_S = -.172, p (2-tailed) > .05
Number of Type 2 conflict points	r_S = -.235, p (2-tailed) > .05	r_S = -.235, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = .000, p (2-tailed) > .05	r_S = .033, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = -.280, p (2-tailed) > .05	r_S = -.280, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = -.382, p (2-tailed) > .05	Variable is a constant
Number of Type 6 conflict points	Variable is a constant	Variable is a constant
Number of Type 7 conflict points	Variable is a constant	Variable is a constant
Number of Type 8 conflict points	Variable is a constant	Variable is a constant
Total number of conflict points RWY-RWY	r_S = -.313, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	r_S = -.095, p (2-tailed) > .05	r_S = -.095, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = -.216, p (2-tailed) > .05	r_S = -.216, p (2-tailed) > .05
Total number of conflict points at the airport	r_S = -.135, p (2-tailed) > .05	r_S = -.135, p (2-tailed) > .05
Total number of segments in conflict with each other	r_S = -.127, p (2-tailed) > .05	r_S = -.127, p (2-tailed) > .05
Number of communication channels	r_S = .025, p (2-tailed) > .05	r_S = .017, p (2-tailed) > .05
Number of frequencies	r_S = -.422, p (2-tailed) > .05	r_S = -.403, p (2-tailed) > .05
Adequacy of equipment	U = .000, p (2-tailed) > .05	U = .000, p (2-tailed) > .05
Adequacy of visual aids	U = .000, p (2-tailed) > .05	U = .000, p (2-tailed) > .05
Complaints about lighting	$H(2)$ = 1.87, p (2-tailed) > .05	$H(2)$ = 1.87, p (2-tailed) > .05
Complaints about marking	$H(2)$ = .379, p (2-tailed) > 05	$H(2)$ = .379, p (2-tailed) > 05
Complaints about signage	$H(2)$ = 1.88, p (2-tailed) >. 05	$H(2)$ = 1.88, p (2-tailed) >. 05
Frequency of maintenance / construction work	$H(4)$ = -.148, p (2-tailed) > .05	$H(4)$ = -.148, p (2-tailed) > .05
Subcontractors working on the airfield	U = 3.00*, p (2-tailed) < .05	U = 3.00*, p (2-tailed) < .05
Requirement of clearances for all vehicle drivers	Variable is a constant	Variable is a constant
Vehicle equipment with radio communication	Variable is a constant	Variable is a constant
Number of runway condition checks	r_S = .387, p (2-tailed) > .05	r_S = -.426, p (2-tailed) > .05
Use of runways as taxiways	$H(2)$ = 3.21, p (2-tailed) > .05	$H(2)$ = 3.21, p (2-tailed) > .05
Engagement in pro-active safety assessments	U = 29.00, p (2-tailed) > .05	U = 29.00, p (2-tailed) > .05
Adequacy of staffing level for airside operations	$H(1)$ = .416, p (2-tailed) > .05	$H(1)$ = .416, p (2-tailed) > .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	$U = 1.50$, p (2-tailed) > .05	$U = 1.50$, p (2-tailed) > .05

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 17: Associations between airport characteristics and the number of total occurrences (per 100,000 movements) – Norway

Variable	Complete data set	Excluding outliers
Average annual movements	r_S = -.579*, p (2-tailed) < .05	r_S = -.335, p (2-tailed) > .05
Altitude	r_S = .214 p (2-tailed) > .05	r_S = .042 p (2-tailed) > .05
Peak number of operations	r_S = -.250, p (2-tailed) > .05	r_S = -.304, p (2-tailed) > .05
Number of runways	r_S = -.365, p (2-tailed) > .05	Variable is a constant
Number of taxiway segments	r_S = -.491, p (2-tailed) > .05	r_S = -.598*, p (2-tailed) < .05
Number of Type 2 conflict points	r_S = -.318, p (2-tailed) > .05	r_S = -.484, p (2-tailed) > .05
Number of Type 3 conflict points	r_S = -.458, p (2-tailed) > .05	r_S = -.457, p (2-tailed) > .05
Number of Type 4 conflict points	r_S = -.274, p (2-tailed) > .05	r_S = -.497, p (2-tailed) > .05
Number of Type 5 conflict points	r_S = .071, p (2-tailed) > .05	Variable is a constant
Number of Type 6 conflict points	Variable is a constant	Variable is a constant
Number of Type 7 conflict points	Variable is a constant	Variable is a constant
Number of Type 8 conflict points	Variable is a constant	Variable is a constant
Total number of conflict points RWY-RWY	r_S = -.084, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	r_S = -.377, p (2-tailed) > .05	r_S = -.407, p (2-tailed) > .05
Total number of conflict points TWY-TWY	r_S = -.455, p (2-tailed) > .05	r_S = -.636*, p (2-tailed) < .05
Total number of conflict points at the airport	r_S = -.496, p (2-tailed) > .05	r_S = -.589*, p (2-tailed) < .05
Total number of segments in conflict with each other	r_S = -.483, p (2-tailed) > .05	r_S = -.569*, p (2-tailed) < .05
Number of communication channels	r_S = -.348, p (2-tailed) > .05	r_S = -.330, p (2-tailed) > .05
Number of frequencies	r_S = -.137, p (2-tailed) > .05	r = -.720, p (2-tailed) < .05
Adequacy of equipment	U = 7.00, p (2-tailed) > .05	U = 5.00, p (2-tailed) > .05
Adequacy of visual aids	U = .000, p (2-tailed) > .05	U = 5.00, p (2-tailed) > .05
Complaints about lighting	$H(2)$ = 1.48, p (2-tailed) > .05	$H(2)$ = 1.53, p (2-tailed) > .05
Complaints about marking	$H(2)$ = 1.43, p (2-tailed) > 05	$H(2)$ = 2.34, p (2-tailed) > 05
Complaints about signage	$H(2)$ = 1.26, p (2-tailed) >. 05	$H(2)$ = 2.34, p (2-tailed) >. 05
Frequency of maintenance / construction work	$H(4)$ = .194, p (2-tailed) > .05	$H(4)$ = -.251, p (2-tailed) > .05
Subcontractors working on the airfield	U = 12.00, p (2-tailed) > .05	U = 12.00, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	Variable is a constant	Variable is a constant
Vehicle equipment with radio communication	Variable is a constant	Variable is a constant
Number of runway condition checks	r_S = -.030, p (2-tailed) > .05	r_S = -.252, p (2-tailed) > .05
Use of runways as taxiways	$H(2)$ = 2.06, p (2-tailed) > .05	$H(2)$ = 4.61, p (2-tailed) > .05
Engagement in pro-active safety assessments	U = 13.00, p (2-tailed) > .05	U = 13.00, p (2-tailed) > .05
Adequacy of staffing level for airside operations	$H(1)$ = .403, p (2-tailed) > .05	$H(1)$ = .138, p (2-tailed) > .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	U = .000, p (2-tailed) > .05	Variable is a constant

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).

Table 18: Associations between airport characteristics and causal factors – Norway

Variable	Complete data set	Excluding outliers
Average annual movements	$H(2) = 34.807^{**}$, p (2-tailed) < .001	$H(2) = 7.223^{*}$, p (2-tailed) < .05
Altitude	$H(2) = 17.111^{**}$, p (2-tailed) < .001	$H(2) = 7.110^{*}$, p (2-tailed) < .05
Peak number of operations	$H(2) = 20.963^{**}$, p (2-tailed) < .001	$H(2) = .250$, p (2-tailed) > .05
Number of runways	$H(2) = 28.632^{**}$, p (2-tailed) < .001	Variable is a constant
Number of taxiway segments	$H(2) = 29.738^{**}$, p (2-tailed) < .001	$H(2) = 6.346^{*}$, p (2-tailed) < .05
Number of Type 2 conflict points	$H(2) = 20.390^{**}$, p (2-tailed) < .001	$H(2) = 20.390^{**}$, p (2-tailed) < .001
Number of Type 3 conflict points	$H(2) = 33.694^{**}$, p (2-tailed) < .001	$H(2) = 7.940^{*}$, p (2-tailed) < .05
Number of Type 4 conflict points	$H(2) = 2.911$, p (2-tailed) > .05	$H(2) = 2.911$, p (2-tailed) > .05
Number of Type 5 conflict points	$H(2) = 5.519$, p (2-tailed) > .05	Variable is a constant
Number of Type 6 conflict points	Variable is a constant	Variable is a constant
Number of Type 7 conflict points	Variable is a constant	Variable is a constant
Number of Type 8 conflict points	Variable is a constant	Variable is a constant
Total number of conflict points RWY-RWY	$H(2) = .209$, p (2-tailed) > .05	Variable is a constant
Total number of conflict points RWY-TWY	$H(2) = 34.614^{**}$, p (2-tailed) < .001	$H(2) = 34.614^{**}$, p (2-tailed) < .001
Total number of conflict points TWY-TWY	$H(2) = 28.654^{**}$, p (2-tailed) < .001	$H(2) = 28.654^{**}$, p (2-tailed) < .001
Total number of conflict points at the airport	$H(2) = 31.969^{**}$, p (2-tailed) < .001	$H(2) = 31.969^{**}$, p (2-tailed) < .001
Total number of segments in conflict with each other	$H(2) = 33.927^{**}$, p (2-tailed) < .001	$H(2) = 33.927^{**}$, p (2-tailed) < .001
Number of communication channels	$H(2) = 28.674^{**}$, p (2-tailed) < .001	$H(2) = .396$, p (2-tailed) > .05
Number of frequencies	$H(2) = 21.976^{**}$, p (2-tailed) < .001	$H(2) = 1.314$, p (2-tailed) > .05
Adequacy of equipment	$X^2 = 5.10$, p (2-tailed) > .05 [a]	$X^2 = 5.100$, p (2-tailed) > .05 [a]
Adequacy of visual aids	$X^2 = 5.10$, p (2-tailed) > .05 [a]	$X^2 = 5.100$, p (2-tailed) > .05 [a]
Complaints about lighting	$X^2 = 35.77^{**}$, p (2-tailed) < .001[a]	$X^2 = 35.277^{**}$, p (2-tailed) < .001[a]
Complaints about marking	$X^2 = 36.181^{**}$, p (2-tailed) < .001	$X^2 = 36.181^{**}$, p (2-tailed) < .001
Complaints about signage	$X^2 = 18.184^{**}$, p (2-tailed) < .05	$X^2 = 18.184^{*}$, p (2-tailed) < .05
Frequency of maintenance / construction work	$X^2 = 26.254^{*}$, p (2-tailed) < .05 [a]	$X^2 = 22.254^{*}$, p (2-tailed) < .05 [a]
Subcontractors working on the airfield	$X^2 = 2.768$, p (2-tailed) > .05	$X^2 = 2.768$, p (2-tailed) > .05
Requirement of clearances for all vehicle drivers	Variable is a constant	Variable is a constant
Vehicle equipment with radio communication	Variable is a constant	Variable is a constant
Number of runway condition checks	$H(2) = 34.057^{**}$, p (2-tailed) < .001	$H(2) = 34.057^{**}$, p (2-tailed) < .001
Use of runways as taxiways	$X^2 = 30.501^{**}$, p (2-tailed) < .001	$X^2 = 30.501^{**}$, p (2-tailed) < .001
Engagement in pro-active safety assessments	$X^2 = 17.584^{**}$, p (2-tailed) < .001	$X^2 = 17.584^{**}$, p (2-tailed) < .001
Adequacy of staffing level for airside operations	$X^2 = 0180$, p (2-tailed) > .05	$X^2 = .180$, p (2-tailed) > .05

Adequacy of training for operational personnel	Variable is a constant	Variable is a constant
Adequacy of training for sub-contractors	X^2 = 10.119*, p (2-tailed) < .05	X^2 = 10.102*, p (2-tailed) < .05

**. Test statistic is significant at the 0.01 level (2-tailed).
*. Test statistic is significant at the 0.05 level (2-tailed).
[a] The Pearson Chi-Square test assumptions are violated.

Appendix IX: Fundamentals of Logistic Regression

1 Method

When entering several predictors into a regression model, the method for entry needs to be selected, with both forced entry and stepwise methods are available. Forced entry is a method in which all predictors are forced into the model simultaneously. It relies on good theoretical reasoning for the inclusion of the chosen predictors. On the other hand, the choices of which predictors are entered into a model in stepwise regressions are based on a mathematical criterion. Two methods can be distinguished: forward and backward stepwise regression. Using a forward method an initial model is defined which contains only the constant, and the predictors are then added to the model based on a specific criterion. The backward methods, on the other hand, begin by placing all predictors in the model and then removing them using removal criteria.

Stepwise methods take many methodologically important decisions out of the hands of the researcher and can lead to over-fitting (i.e. having too many variables in the model that make little contribution to predicting the outcome) and under-fitting (i.e. leaving out important predictors). Forced entry based the selection of meaningful variables is preferable, therefore, and stepwise methods should be avoided except for exploratory studies (Field, 2009). Based on this criticism of stepwise methods the forced entry method has been chosen for the analysis in this thesis.

2 Assumptions

A logistic regression requires the following assumptions to be true (Agresti, 2007; Field, 2009):

1) Linearity: Ordinary regression assumes a linear relationship between the DV and the IVs. As introduced in the last section, this assumption is violated in logistic regression and therefore the log (i.e. logit) of the data is used. In logistic regression, the assumption of linearity assumes a linear relationship between any continuous IV and the logit of the outcome variable.

2) Independence of errors: The cases of data should not be related (e.g. repeated measures design where the same people are measured at different points in time). A violation of this assumption produces overdispersion, a situation in which the

observed variance is bigger than would be expected for the logistic regression model.

3) Multicollinearity: IVs should not be too highly correlated.

Ordered logistic regression assumes in addition:

4) Proportional odds: The slope coefficients in an ordered logistic regression model are the same across the response categories. That means the relationship between any two pairs of outcome groups is statistically the same.

3 Assessing the Model Fit

The statistical package SPSS was used to estimate the logistic regression models presented in this thesis and this section explains how to assess the output of the SPSS logistic regression estimation tables.

The overall fit of the estimated model is assessed using the log-likelihood statistic, also referred to as -2LL (SPSS output: *-2 Log likelihood*). The log-likelihood statistic is an indicator of how much unexplained information there is after the model has been fitted. Large values indicate a poor fitting statistical model, since the larger the value the more unexplained observations there are. To make the interpretation of the log-likelihood statistic meaningful, the -2LL of the fitted model is compared against a baseline model. The baseline model is the model that provides the best prediction when nothing but the values of the outcome variable are known (i.e. the logistic regression model when only the constant is included). In logistic regression this corresponds to the prediction of the outcome category that occurred most often. A reduction in the -2LL from the baseline model to the fitted model indicates that the new model is better at predicting than the baseline model. The difference in the -2LL values shows the reduction in the inaccuracy of the model resulting from fitting the regression model to the data, i.e. how much new variance has been explained by the fitted model. The significance of this reduction in unexplained variance is tested using the chi-square statistic (X^2). A significant X^2 ($p < .05$) indicates that the estimated model explains a significant amount of the original variability.

The log-likelihood statistic indicates whether a model provides a better fit than the baseline model. This does not necessarily mean, however, that the model is a good fit to the data. In multinomial logistic regression the Pearson and Deviance Chi-Squared Tests

are used to assess the model's goodness of fit (SPSS output: *Pearson, Deviance*). These statistics test whether the predicted values differ significantly from the observed values. If the test statistics are not significant ($p > .05$) then the predicted values are not significantly different from the observed values, i.e. the model is a good fit. An alternative is the Hosmer and Lemeshow Test, which is mainly used to assess the goodness of fit for binomial logistic regression models. Its interpretation is the same.

In addition, the Cox and Snell's R^2_{CS} and Nagelkerke's R^2_N should be assessed (SPSS output: *Cox and Snell, Nagelkerke*). Both statistics show the proportion of improvement due to the model, i.e. how much the badness of fit improves as a result of the inclusion of the IVs. R^2_{CS} and R^2_N can vary between 0 and 1. A value of 0 indicates that the IVs are useless in predicting the DV and a value of 1 indicates that the model predicts the DV perfectly.

The *b*-values (SPSS output: *B*) are the estimated coefficients of the IVs included in the model. The b-value represents the change in the logit of the DV associated with one-unit change in the IV. To assess whether an IV is making a significant contribution to the prediction of the DV the Wald statistic is used (SPSS output: *Wald*). The Wald statistic tests whether the *b*-coefficient for an IV is significantly different from 0. If so ($p < .05$), then the IV is making a significant contribution to the prediction of the DV.

Crucial to the interpretation of logistic regression models is the interpretation of the odds ratio (SPSS output: *Exp(B)*). The odds ratio is an indicator of the change in odds resulting from a unit change in the IV. The odds of an event occurring are defined as the probability of an event occurring divided by the probability of that event not occurring. A value greater than 1 indicates that as the IV increases the odds of the DV occurring increase. In contrast, a value less than 1 indicates that as the IV increases, the odds of the outcome occurring decrease. Section 0 will give examples for the interpretation of logistic regression models (Field, 2009).

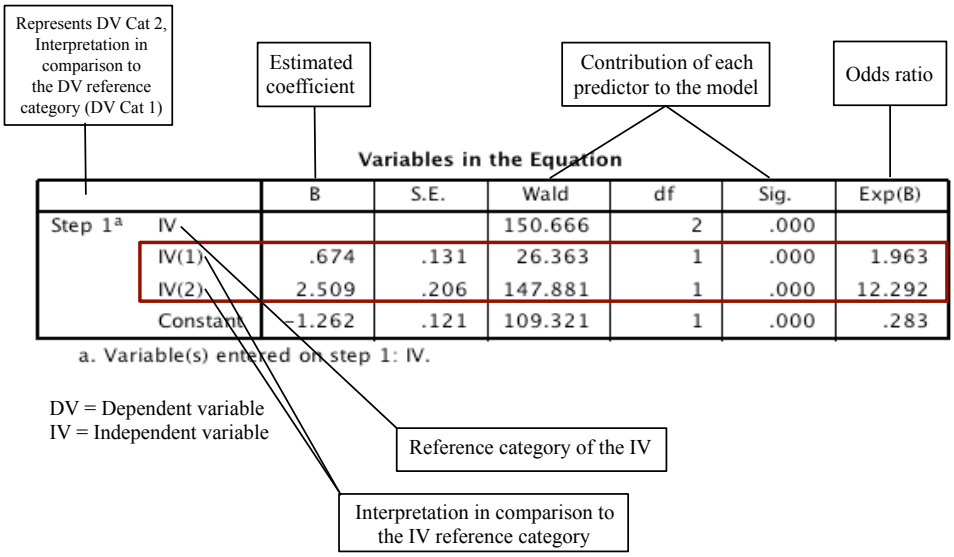
4 Interpretation

The interpretation of the SPSS output, and in particular the odds ratio, is not straightforward. The following paragraphs provide examples for interpreting the SPSS parameter estimates output for binary, multinomial and ordinal regression models.

Table 1 shows an example of the SPSS output for a binary logistic regression. The DV is a binary variable with two categories (DV Cat 1, DV Cat 2). The lowest coded variable

(DV Cat 1) is set as the reference category and therefore, DV Cat 2 must be interpreted in comparison to this reference category. The IV is a nominal categorical variable with three categories (IV, IV(1), IV(2)). IV is set as reference category and therefore IV(1) and IV(2) must be interpreted in comparison to this reference category.

Table 1: Example SPSS parameter estimates output for the binomial logistic regression



The B-value represents the estimated coefficient. It represents the change in the logit of the DV associated with a one unit change in the IV. For instance, a one unit increase in IV(1) is associated with a .674 increase of the logit of the outcome variable.

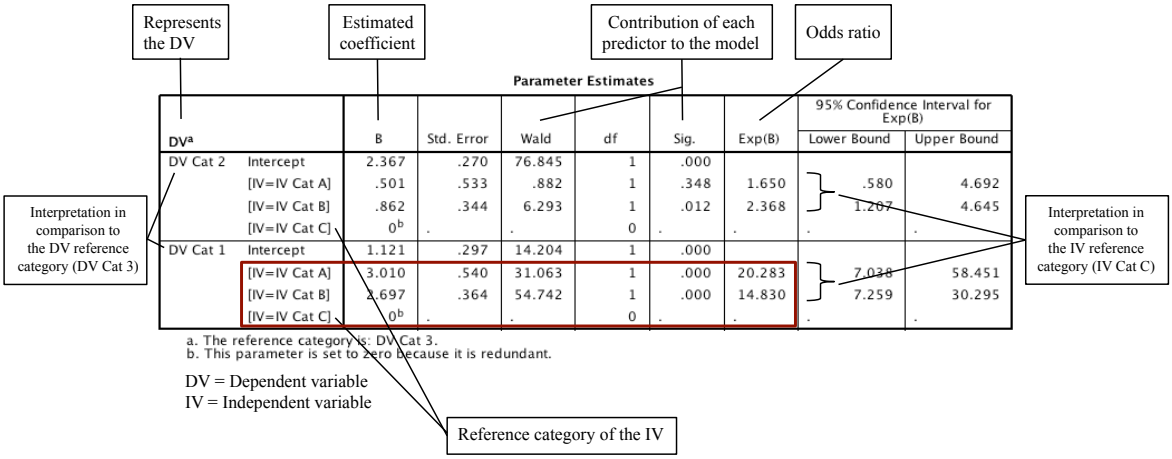
The Wald statistic is used to assess the contribution of individual predictors. In the example in Table 1 all IVs are significant predictors ($p < .001$).

The interpretation of the odds ratio (Exp(B)) is important. The odds ratio indicates the change in odds that results from a unit change in the IV. For categorical predictors the interpretation is as follows: the odds of IV(1) having the response category DV Cat 2 (rather than the reference category DV Cat 1) is 1.963 in comparison to the reference category IV. In other words, IV(1) compared to its reference category (IV) is almost twice as likely to have the outcome response DV Cat 2 rather than DV Cat 1. Similarly, IV(2) compared to its reference category IV is 12.29 times more likely to have the outcome response DV Cat 2 rather than DV Cat 1.

Table 2 shows the SPSS output for the parameter estimates for a multinominal logistic regression model. The DV is a nominal categorical variable with three outcome categories (DV Cat 1, DV Cat 2, DV Cat 3). DV Cat 3 is set as the reference category to which all

other DV categories are compared. This model contains only one IV. The IV is also a nominal categorical variable with three categories (IV Cat A, IV Cat B, IV Cat C). For the predictor IV Cat C is set as the reference category. Therefore, all other IV categories are interpreted in comparison to this reference category.

Table 2: Example SPSS parameter estimates output for the multinomial logistic regression



Parameter Estimates

DV[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B) Lower Bound	Upper Bound
DV Cat 2	Intercept	2.367	.270	76.845	1	.000			
	[IV=IV Cat A]	.501	.533	.882	1	.348	1.650	.580	4.692
	[IV=IV Cat B]	.862	.344	6.293	1	.012	2.368	1.207	4.645
	[IV=IV Cat C]	0[b]	.	.	0	.	.	.	.
DV Cat 1	Intercept	1.121	.297	14.204	1	.000			
	[IV=IV Cat A]	3.010	.540	31.063	1	.000	20.283	7.038	58.451
	[IV=IV Cat B]	2.697	.364	54.742	1	.000	14.830	7.259	30.295
	[IV=IV Cat C]	0[b]	.	.	0	.	.	.	.

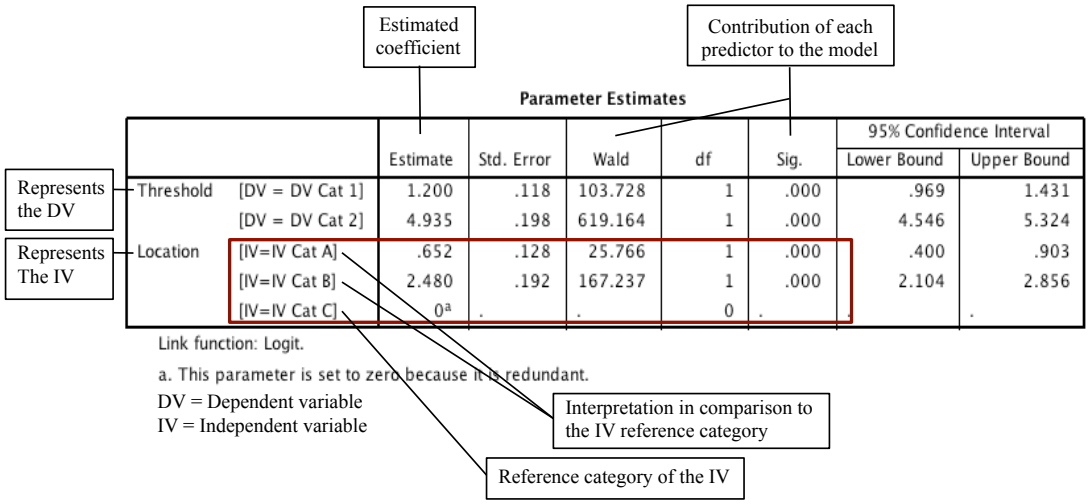
a. The reference category is: DV Cat 3.
b. This parameter is set to zero because it is redundant.

First, the significance of the IVs is assessed using the Wald statistic. For instance, both IV Cat A and IV Cat B are significant predictors for DV Cat 1 ($p < .001$). The B-value shows the estimated coefficients. A positive B-value indicates that the cases in an IV category have a higher probability than cases in the IV reference category, to be classified as the considered DV category compared to the DV reference category. Continuing the example of DV Cat 1, cases in both IV Cat A and IV Cat B have a higher probability to be classified as DV Cat 1 (rather than DV Cat 3) in comparison to cases in the reference category IV Cat C.

The odds ratio (Exp(B)) shows the change of odds resulting from one unit change in the IV. For categorical predictors the odds ratio can be interpreted as follows. IV Cat A compared to its reference category IV Cat C is 20 times as likely to have DV Cat 1 (rather than DV Cat 3). Similarly, IV Cat B compared to its reference category IV Cat C is almost 15 times more likely to have DV Cat 1 (rather than DV Cat 3).

Table 3 provides an example for the output interpretation of the parameter estimates for an ordinal logistic regression model.

Table 3: Example SPSS parameter output for the multinomial logistic regression



"Threshold" represents the DV. The DV, in this case, is an ordinal variable with three categories (DV Cat 1, DV Cat 2, DV Cat 3). DV Cat 3 is set as reference category. The IVs are shown under "Location". This model uses only one IV to predict the outcome. The IV is a nominal categorical variable with three categories (IV Cat A, IV Cat B, IV Cat C). IV Cat 3 is set as reference category. This means that all parameter estimates of the IV are interpreted in comparison to this reference category.

First, the significance of the contribution of each IV to the model is assessed. Both, IV Cat A and IV Cat B are statistically significant predictors of the outcome ($p < .001$). Here, the interpretation of the odds ratio is crucial. The odds ratio indicates how one unit change in the IV changes the odds of change of one level in the DV; in other words, the odds of being entered into a higher tier, or response category, in the ordinal outcome. Due to the assumption of proportional odds, the change in odds is the same for all levels of the DV. This means the odds ratio is the same for, e.g., the change from DV Cat 1 to DV Cat 2, and the change from DV Cat 2 to DV Cat 3.

"Estimate" represents the estimated coefficient. The ordinal logistic regression output does not automatically give the odds ratio. It can be calculated by taking the exponent from the Estimate. The Estimate for IV Cat A is .652. The exponent of .652 is 1.92 (odds ratio). The odds of IV Cat A being entered into a higher tier (DV category) are 1.92 the odds for IV Cat C. In other words, the odds of IV Cat A achieving a higher tier are approximately twice the odds for IV Cat C. The Estimate of IV Cat B is 2.480 and the associated odds ratio is 11.94. The odds of IV Cat B being entered for a higher tier are approximately

twelve times the odds of IV Cat C being entered for a higher tier (Field, 2009; National Centre for Research Methods, 2011).

Appendix X: Supplementary Analysis to Chapter 11

Table 1: Sample descriptives

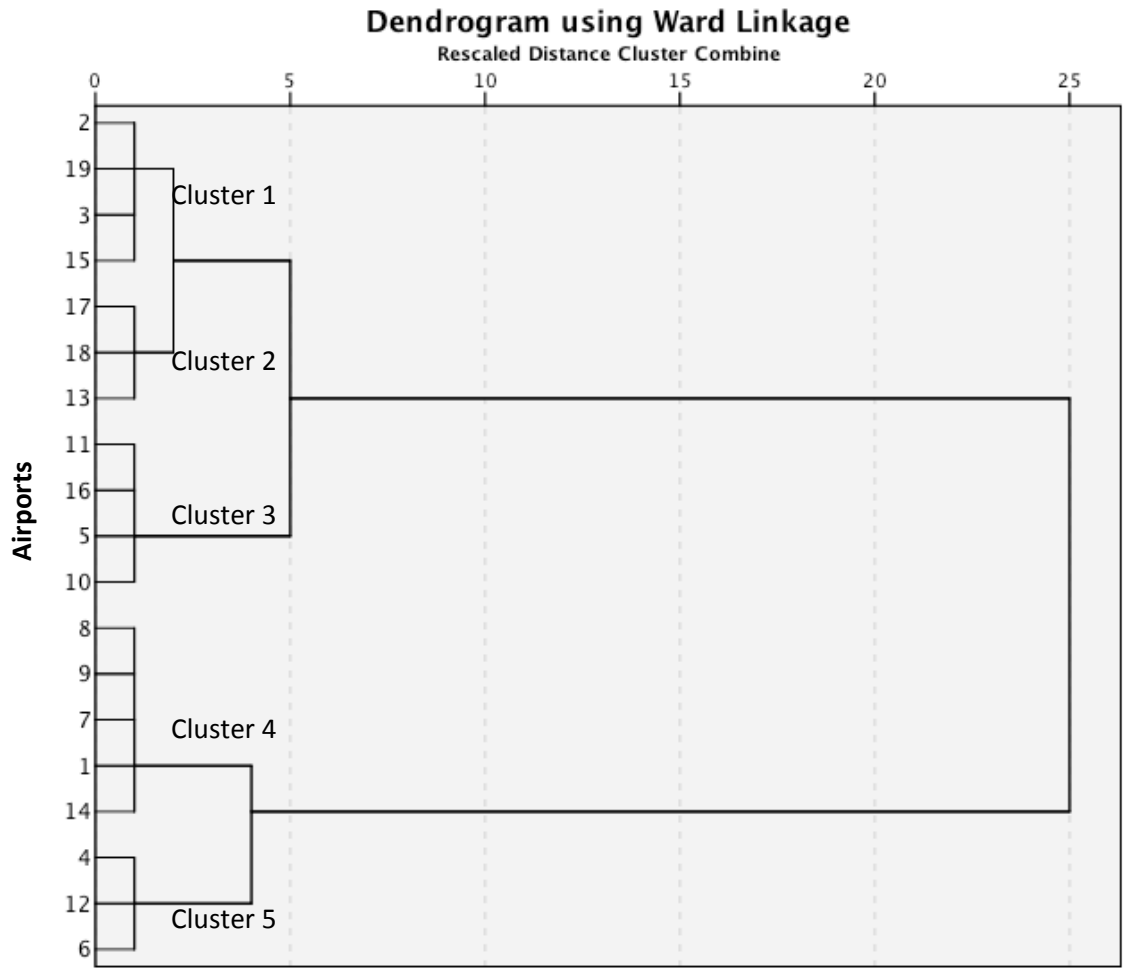
Variable	Data type	Sample size	Minimum value	Maximum value	Range	Mean	Standard deviation
Average annual movements	Continuous	19	47220	979360	932140	405157.83	263506.956
Peak number of operations	Continuous	19	40	279	139	99.75	65.588
Number of runways	Continuous	19	1	7	6	3.84	1.675
Number of taxiway segments	Continuous	19	8	327	319	135.79	86.720
Number of Type 2 conflict points RWY / RWY	Continuous	19	0	1	1	.05	.229
Number of Type 2 conflict points RWY / TWY	Continuous	19	0	7	7	2.11	1.941
Number of Type 2 conflict points TWY / TWY	Continuous	19	2	14	12	7.74	3.088
Total number of Type 2 conflict points	Continuous	19	4	17	13	9.89	3.695
Number of Type 3 conflict points RWY / RWY	Continuous	19	0	1	1	.11	.315
Number of Type 3 conflict points RWY / TWY	Continuous	19	1	34	33	15.68	8.926
Number of Type 3 conflict points TWY / TWY	Continuous	19	2	86	84	36.74	25.798
Total number of Type 3 conflict points	Continuous	19	3	114	111	52.53	33.140
Number of Type 4 conflict points RWY / RWY	Continuous	19	0	6	6	.89	1.449
Number of Type 4 conflict points RWY / TWY	Continuous	19	1	43	42	12.74	9.780
Number of Type 4 conflict points TWY / TWY	Continuous	19	0	41	41	15.74	11.160
Total number of Type 4 conflict points	Continuous	19	1	84	83	29.37	19.825
Number of Type 5 conflict points RWY / RWY	Continuous	19	0	0	0	.00	.00
Number of Type 5 conflict points RWY / TWY	Continuous	19	0	3	3	.84	1.167
Number of Type 5 conflict points TWY / TWY	Continuous	19	0	18	18	2.32	4.097
Total number of Type 5 conflict points	Continuous	19	0	19	19	3.16	4.362
Number of Type 6 conflict points RWY / RWY	Continuous	19	0	0	0	.00	.00
Number of Type 6 conflict points RWY / TWY	Continuous	19	0	2	2	.26	.562
Number of Type 6 conflict points TWY / TWY	Continuous	19	0	1	1	.16	.375
Total number of Type 6 conflict points	Continuous	19	0	2	2	.42	.838
Number of Type 7 conflict points RWY / RWY	Continuous	19	0	0	0	.00	.00
Number of Type 7 conflict points RWY / TWY	Continuous	19	0	3	0	.16	.688

Number of Type 7 conflict points TWY / TWY	Continuous	19	0	0	0	.00	.00
Total number of Type 7 conflict points	Continuous	19	0	3	0	.16	.688
Number of Type 8 conflict points RWY / RWY	Continuous	19	0	0	0	.00	.00
Number of Type 8 conflict points RWY / TWY	Continuous	19	0	0	0	.00	.00
Number of Type 8 conflict points TWY / TWY	Continuous	19	0	0	0	.00	.00
Total number of Type 8 conflict points	Continuous	19	0	0	0	.00	.00
Total number of conflict points RWY/RWY	Continuous	19	0	7	7	1.05	1.682
Total number of conflict points RWY/TWY	Continuous	19	2	79	77	29.53	18.292
Total number of conflict points TWY/TWY	Continuous	19	4	128	124	62.68	38.187
Total number of conflict points at the airport	Continuous	19	6	207	201	93.26	54.930
Total number of segments in conflict with each other	Continuous	19	21	777	756	315.05	193.779

Table 2: Parameter estimates airport characteristics vs. severity - excluding outliers

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity	Average annual movements	.000	.000	11.689	1	.001	1.000
Cat C	Constant	-.804	.268	9.016	1	.003	.447
(High)	R^2 = .030 (Hosmer&Lemeshow), .042 (Cox&Snell), .056 (Nagelkerke). Model X^2 = 12.193, p < .001.						
Severity	Peak number of operations	.007	.002	16.789	1	.000	1.007
Cat C	Constant	-.756	.220	11.751	1	.001	.470
(High)	R^2 = .027 (Hosmer&Lemeshow), .046 (Cox&Snell), .061 (Nagelkerke). Model X^2 = 10.683, p < .001.						
Severity	Number of runways	.419	.084	25.133	1	.000	1.521
Cat C	Constant	-1.938	.408	22.546	1	.000	.144
(High)	R^2 = .071 (Hosmer&Lemeshow), .094 (Cox&Snell), .125 (Nagelkerke). Model X^2 = 28.009, p < .001.						
Severity	Number of taxiway segments	.005	.001	14.386	1	.000	1.005
Cat C	Constant	-.939	.279	11.371	1	.001	.391
(High)	R^2 = .038 (Hosmer&Lemeshow), .052 (Cox&Snell), .069 (Nagelkerke). Model X^2 = 15.142, p < .001.						
Severity	Number of type 2 RWY/TWY conflict points	-.183	.092	3.981	1	.046	.833
Cat C	Constant	.289	.210	1.906	1	.167	1.336
(High)	R^2 = .010 (Hosmer&Lemeshow), .016 (Cox&Snell), .021 (Nagelkerke). Model X^2 = 4.080, p < .05.						
Severity	Number of type 2 TWY/TWY conflict points	.102	.044	5.290	1	.021	1.107
Cat C	Constant	-.927	.426	4.736	1	.030	.396
(High)	R^2 = .013 (Hosmer&Lemeshow), .019 (Cox&Snell), .025 (Nagelkerke). Model X^2 = 5.415, p < .05.						
Severity	Total number of type 2 conflict points	.056	.033	2.826	1	.093	1.057
Cat C	Constant	-.635	.404	2.473	1	.116	.530
(High)	R^2 = .000 (Hosmer&Lemeshow), .010 (Cox&Snell), .013 (Nagelkerke). Model X^2 = 2.854, p > .05.						
Severity	Number of type 3 RWY/TWY conflict points	.070	.015	20.499	1	.000	1.072
Cat C	Constant	-1.410	.339	17.272	1	.000	.244
(High)	R^2 = .056 (Hosmer&Lemeshow), .076 (Cox&Snell), .101 (Nagelkerke). Model X^2 = 22.393, p < .001.						
Severity	Number of type 3 TWY/TWY conflict points	.011	.005	5.431	1	.020	1.011
Cat C	Constant	-.517	.257	4.036	1	.045	.596
(High)	R^2 = .013 (Hosmer&Lemeshow), .019 (Cox&Snell), .026 (Nagelkerke). Model X^2 = 5.508, p < .05.						
Severity	Total number of type 3 conflict points	.012	.004	9.505	1	.002	1.012
Cat C	Constant	-.794	.289	7.560	1	.006	.452
(High)	R^2 = .024 (Hosmer&Lemeshow), .034 (Cox&Snell), .045 (Nagelkerke). Model X^2 = 9.766, p < .05.						
Severity	Number of type 4 RWY/RWY conflict points	.076	.163	.216	1	.642	1.079
Cat C	Constant	-.094	.161	.340	1	.560	.911
(High)	R^2 = .000 (Hosmer&Lemeshow), .001 (Cox&Snell), .001 (Nagelkerke). Model X^2 = .216, p > .05.						
Severity	Number of type 4 RWY/TWY conflict points	.053	.023	5.171	1	.023	1.054
Cat C	Constant	-.803	.341	5.538	0	.019	.448
(High)	R^2 = .013 (Hosmer&Lemeshow), .021 (Cox&Snell), .027 (Nagelkerke). Model X^2 = 5.301, p < .05.						
Severity	Number of type 4 TWY/TWY conflict points	.050	.012	15.955	1	.000	1.051
Cat C	Constant	-.937	.266	12.427	1	.000	.392
(High)	R^2 = .044 (Hosmer&Lemeshow), .060 (Cox&Snell), .080 (Nagelkerke). Model X^2 = 17.503, p < .001.						
Severity	Total number of type 4 conflict points	.037	.011	11.667	1	.001	1.038
Cat C	Constant	-1.269	.374	11.535	1	.001	.281
(High)	R^2 = .031 (Hosmer&Lemeshow), .048 (Cox&Snell), .064 (Nagelkerke). Model X^2 = 12.445, p < .001.						
Severity	Number of type 5 RWY/TWY conflict points	.146	.099	2.168	1	.141	1.158
Cat C	Constant	-.135	.156	.748	1	.387	.874
(High)	R^2 = .000 (Hosmer&Lemeshow), .008 (Cox&Snell), .010 (Nagelkerke). Model X^2 = 2.195, p > .05.						
Severity	Number of type 5 TWY/TWY conflict points	.105	.080	1.712	1	.191	1.110
Cat C	Constant	-.267	.187	2.045	1	.153	.765
(High)	R^2 = .004 (Hosmer&Lemeshow), .007 (Cox&Snell), .009 (Nagelkerke). Model X^2 = 1.724, p > .05.						
Severity	Total number of type 5 conflict points	.132	.065	4.093	1	.043	1.141
Cat C	Constant	-.451	.221	4.169	1	.041	.637
(High)	R^2 = .010 (Hosmer&Lemeshow), .016 (Cox&Snell), .022 (Nagelkerke). Model X^2 = 4.152, p < .05.						
Severity	Number of type 6 RWY/TWY conflict points	.479	.233	4.239	1	.040	1.614
Cat C	Constant	-.148	.142	1.079	1	.299	.863

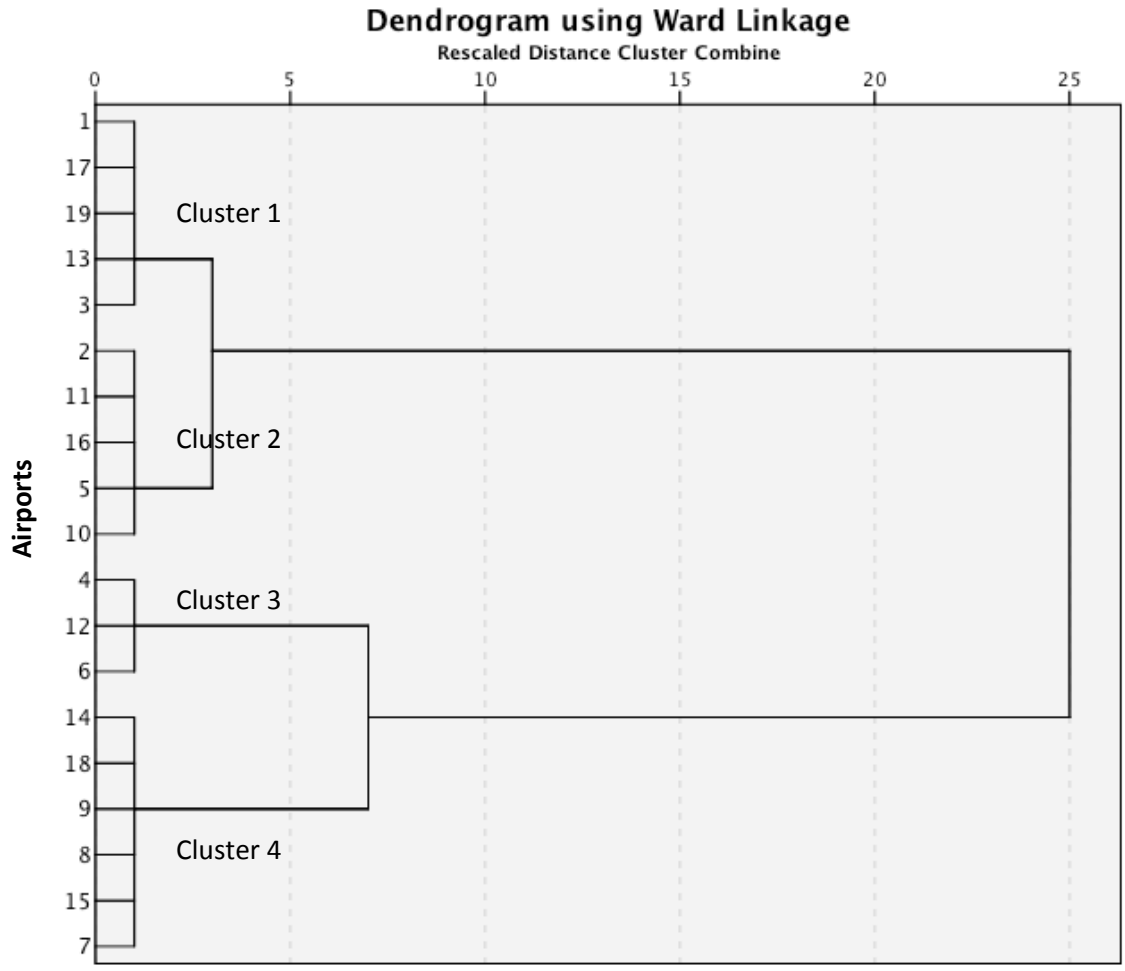
(High)	R^2 = .011 (Hosmer&Lemeshow), .015 (Cox&Snell), .020 (Nagelkerke). Model X^2 = 4.348, p < .05.						
Severity Cat C (High)	Number of type 6 TWY/TWY conflict points	.565	.265	4.541	1	.033	1.760
	Constant	-.150	.141	1.117	1	.290	.861
	R^2 = .011 (Hosmer&Lemeshow), .016 (Cox&Snell), .021 (Nagelkerke). Model X^2 = 4.613, p < .05.						
Severity Cat C (High)	Total number of type 6 conflict points	.285	.129	4.857	1	.028	1.330
	Constant	-.165	.144	1.317	1	.251	.848
	R^2 = .012 (Hosmer&Lemeshow), .017 (Cox&Snell), .023 (Nagelkerke). Model X^2 = 4.931, p < .05.						
Severity Cat C (High)	Total number of RWY/RWY conflict points	.070	.153	.209	1	.647	1.072
	Constant	-.093	.161	.336	1	.562	.911
	R^2 = .000 (Hosmer&Lemeshow), .001 (Cox&Snell), .001 (Nagelkerke). Model X^2 = .209, p > .05.						
Severity Cat C (High)	Total number of RWY/TWY conflict points	.036	.010	11.737	1	.001	1.036
	Constant	-1.299	.380	11.694	1	.001	.273
	R^2 = .031 (Hosmer&Lemeshow), .048 (Cox&Snell), .064 (Nagelkerke). Model X^2 = 12.435, p < .001.						
Severity Cat C (High)	Total number of TWY/TWY conflict points	.011	.003	11.470	1	.001	1.012
	Constant	-.904	.297	9.250	1	.002	.405
	R^2 = .030 (Hosmer&Lemeshow), .041 (Cox&Snell), .055 (Nagelkerke). Model X^2 = 11.856, p < .001.						
Severity Cat C (High)	Total number of conflict points at the airport	.009	.002	14.689	1	.000	1.009
	Constant	-1.087	.312	12.134	1	.000	.337
	R^2 = .039 (Hosmer&Lemeshow), .053 (Cox&Snell), .071 (Nagelkerke). Model X^2 = 15.530, p < .001.						
Severity Cat C (High)	Total number of segments in conflict with each other	.003	.001	14.921	1	.000	1.003
	Constant	-1.034	.296	12.183	1	.000	.356
	R^2 = .040 (Hosmer&Lemeshow), .055 (Cox&Snell), .073 (Nagelkerke). Model X^2 = 16.011, p < .001.						



Description of clusters:

Cluster 1: 3-4 runways; 8-13 type 3 RWY/TWY segments
Cluster 2: 3-4 runways; 15-16 type 3 RWY/TWY segments
Cluster 3: 1-3 runways; 5-6 type 3 RWY/TWY segments
Cluster 4: 4-6 runways; 19-22 type 3 RWY/TWY segments
Cluster 5: 5-7 runways; 27-34 type 3 RWY/TWY segments

Figure 1: Number of runways / number of taxiway segments dendogram



Description of clusters:

Cluster 1: 3-4 runways; 84-113 TWY segments
Cluster 2: 1-3 runways; 8-48 TWY segments
Cluster 3: 5-7 runways; 227-247 TWY segments
Cluster 4: 3-5 runways; 214-191 TWY segments

Figure 2: Number of runways / number of type 3 RWY/TWY conflict points dendogram

Table 3: Parameter estimates airport characteristics level 1 vs. severity – excluding outliers

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of runways	.511	.143	12.700	1	.000	1.666
	Number of taxiways	.010	.011	.829	1	.362	1.010
	Total number of conflict points	-.020	.020	.984	1	.321	.980
	Constant	-1.780	.445	15.963	1	.000	.169

R^2 = .074 (Hosmer&Lemeshow), .097 (Cox&Snell), .130 (Nagelkerke). Model X^2 = 29.102, p < .001.

Table 4: Parameter estimates airport characteristics level 2 vs. severity – excluding outliers

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Total number of RWY/RWY conflict points	.376	.179	4.435	1	.035	1.456
	Total number of RWY/TWY conflict points	.033	.032	1.085	1	.298	1.033
	Total number of TWY/TWY conflict points	.003	.012	.057	1	.811	1.003
	Constant	-1.762	.448	15.504	1	.000	.172

R^2 = .037 (Hosmer&Lemeshow), .067 (Cox&Snell), .090 (Nagelkerke). Model X^2 = 15.740, p < .001.

Table 5: Parameter estimates airport characteristics level 3 (RWY/RWY conflict points) vs. severity – excluding outliers

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 4 RWY/RWY conflict points	.076	.163	.216	1	.642	1.079
	Constant	-.094	.161	.340	1	.560	.911

R^2 = .000 (Hosmer&Lemeshow), .001 (Cox&Snell), .001 (Nagelkerke). Model X^2 = .216, p > .05.

Table 6: Parameter estimates airport characteristics level 3 (RWY / TWY conflict points) vs. severity – excluding outliers

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 2 RWY/TWY conflict points	-.128	.117	1.191	1	.275	.880
	Number of type 3 RWY/TWY conflict points	.120	.038	9.985	1	.002	1.127
	Number of type 4 RWY/TWY conflict points	-.082	.046	3.118	1	.077	.921
	Number of type 5 RWY/TWY conflict points	-.034	.134	.064	1	.800	.967
	Number of type 6 RWY/TWY conflict points	.495	.344	2.069	1	.150	1.641
	Constant	-1.067	.501	4.530	1	.033	.344

R^2 = .044 (Hosmer&Lemeshow), .074 (Cox&Snell), .098 (Nagelkerke). Model X^2 = 13.335, p < .05.

Table 7: Parameter estimates airport characteristics level 3 (TWY / TWY conflict points) vs. severity – excluding outliers

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 2 TWY/TWY conflict points	.078	.055	2.012	1	.156	1.081
	Number of type 3 TWY/TWY conflict points	-.008	.008	.969	1	.325	.992
	Number of type 4 TWY/TWY conflict points	.064	.032	4.180	1	.041	1.067
	Number of type 5 TWY/TWY conflict points	-.060	.170	.124	1	.725	.942
	Number of type 6 TWY/TWY conflict points	.334	.617	.292	1	.589	1.396
	Constant	-1.508	.518	8.485	1	.004	.221

R^2 = .037 (Hosmer&Lemeshow), .057 (Cox&Snell), .076 (Nagelkerke). Model X^2 = 14.859, p < .05.

Table 8: Parameter estimates airport characteristics level 3 (type 4 conflict points) vs. severity – excluding outliers

Event		B	Std. Error	Wald	df	Sig.	Exp(B)
Severity Cat C (High)	Number of type 4 RWY/RWY conflict points	.607	.204	8.870	1	.003	1.835
	Number of type 4 RWY/TWY conflict points	-.037	.034	1.164	1	.281	.964
	Number of type 4 TWY/TWY conflict points	.096	.026	13.571	1	.000	1.101
	Constant	-1.754	.443	15.692	1	.000	.173

R^2 = .053 (Hosmer&Lemeshow), .089 (Cox&Snell), .119 (Nagelkerke). Model X^2 = 21.222, p < .001.

Table 9: Distribution of causal factors (Level 3) across airports

Airport*	Pilot - competence	Pilot - communication	Pilot – situational awareness	Pilot – human reliability	Pilot – Procedures	ATC - competence	ATC – situational awareness	ATC – human reliability	ATC - communication	ATC – team operations	V/PD – resources	V/PD – human reliability	V/PD - communication	Airport management	Airport operations	Total
A	4	14	0	31	0	3	0	9	0	1	0	10	3	0	0	75
B	0	5	3	14	0	0	3	2	3	0	0	15	0	0	3	48
C	0	4	0	16	0	0	1	6	6	1	0	5	0	0	0	39
D	0	14	2	14	0	0	0	1	1	0	0	5	0	0	0	37
E	1	0	0	6	0	0	0	3	0	0	0	4	0	0	0	14
F	0	5	2	6	0	0	0	1	0	1	0	2	0	0	0	17
G	0	10	0	40	2	0	0	5	2	4	0	9	1	0	0	73
H	0	1	1	10	0	0	2	0	1	0	0	0	0	0	0	15
I	0	11	3	41	4	0	2	3	0	0	0	13	1	0	0	78
J	0	1	0	5	0	0	0	0	0	0	0	1	0	0	0	7
K	1	2	0	9	0	0	0	5	0	0	0	0	0	0	0	17
L	0	1	1	3	0	0	0	1	1	0	1	2	0	0	0	10
M	0	2	1	5	0	0	0	0	0	0	0	1	0	0	0	9
N	0	3	0	2	0	0	0	0	1	1	0	1	0	0	0	8
O	0	1	0	1	0	0	0	1	0	0	0	1	0	0	0	4
P	1	3	0	4	0	0	0	1	0	0	0	0	0	1	0	10
Q	0	4	0	7	0	0	0	0	0	0	0	5	0	0	0	16
R	0	4	0	34	8	0	1	0	0	0	0	0	0	0	0	47
Total	7	85	13	248	14	3	9	38	15	8	1	74	5	1	3	524

*The airports are shown in descending order based on their average annual movements.

Table 10: Parameter estimates Airport characteristics (AC) vs. causal factors (CF) (Level 1 and 3)

	AC vs. CF Level 1*		**AC vs. CF pilot Level 3 – pilot communication vs. others****		**AC vs. CF pilot Level 3 – pilot human reliability vs. others****		**AC vs. CF ATC Level 3 – ATC communication vs. others****		**AC vs. CF ATC Level 3 – ATC human reliability vs. others****		**C vs. CF V/PD Level 3 – V/PD human reliability vs. others****	
Airport characteristics	**LR X^2 Sign.**	**Goodness-of-fit**	**LR X^2 Sign.**	**Goodness-of-fit**	**LR X^2 Sign.**	**Goodness-of-fit**	**LR X^2 Sign.**	**Goodness-of-fit**	**LR X^2 Sign.**	**Goodness-of-fit**	**LR X^2 Sign.**	**Goodness-of-fit**
Average annual movements	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Peak number of operations	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Number of runways	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of taxiway segments	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 2 conflict points RWY / TWY	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 2 conflict points TWY / TWY	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Total number of Type 2 conflict points	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 3 conflict points RWY / TWY	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 3 conflict points TWY / TWY	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Total number of Type 3 conflict points	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 4 conflict points RWY / RWY	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 4 conflict points RWY / TWY	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Number of Type 4 conflict points TWY / TWY	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Total number of Type 4 conflict points	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 5 conflict points RWY / TWY	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Number of Type 5 conflict points TWY / TWY	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Total number of Type 5 conflict points	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗

Number of Type 6 conflict points RWY / TWY	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Number of Type 6 conflict points TWY / TWY	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Total number of Type 6 conflict points	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
Total number of conflict points RWY/RWY	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Total number of conflict points RWY/TWY	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Total number of conflict points TWY/TWY	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Total number of conflict points at the airport	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Total number of segments in conflict with each other	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

* Multinomial logistic regression
** Binomial logistic regression