A FRAMEWORK TO ASSESS THE ABILITY OF AUTOMATION TO DELIVER CAPACITY TARGETS IN EUROPEAN AIRSPACE

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This work is dedicated to my parents Pilar Arnedo and Javier Tobaruela

All I have and will accomplish is possible thanks to their love and efforts in offering me the best possible education
I hereby declare that the entire work presented in this thesis has been personally carried out. Where sources of information or the work of others have been used, they are fully cited and referenced and/or appropriate acknowledgement is given.

Gonzalo Tobaruela Arnedo
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ABSTRACT

The maximum number of flights that the Air Traffic Management (ATM) system can safely and efficiently control over a period of time i.e. airspace capacity, has become a limitation over the last decade, due to a rapid increase in air traffic activity. Therefore, the ATM system in developed countries is undergoing a series of modernisation initiatives to ensure that the future ATM system is able to provide sufficient capacity to safely meet future air traffic demand. As a result, there is a need to assess if the proposed changes can effectively be translated into the desired increase in capacity.

This thesis addresses this issue by developing an en-route airspace capacity estimation framework, able to measure the impact of future ATM system modernisation deployments on airspace capacity. In order to do this, it identifies the key airspace capacity drivers for current and future operations, focussing on three areas: air traffic controller workload, air traffic predictability and Air Traffic Control (ATC) centre cost-efficiency.

In each of the three framework areas, the research develops methodologies that overcome the deficiencies of existing capacity estimation techniques. This leads to an innovative multi-dimensional approach to airspace capacity estimation, able to reflect the different relationships of airspace capacity with the framework areas.

The framework quantifies the relationship between the ATC centre planning process accuracy and airspace capacity. It estimates the effect of increased predictability on airspace capacity through the performance of the Airspace Management and Air Traffic Flow & Capacity Management functions. Finally, it computes air traffic controller workload with considerable accuracy (up to 80% of the actual workload) during medium-low workload scenarios and reflects the workload trend (Spearman’s rank coefficient = 0.72) during high workload scenarios.
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CHAPTER 1  Introduction ................................................................. 43

1.1  Background................................................................................. 43

1.2  Aims and Objectives................................................................. 45

1.3  Thesis Structure ....................................................................... 46

CHAPTER 2  Fundamentals of Air Traffic Management ......................... 51

2.1  Evolution of Air Traffic Management (ATM) ............................. 51

2.2  Stakeholders of Air Traffic Management ................................ 54

   2.2.1  Airspace users ................................................................. 55

      2.2.1.1  Commercial aviation .............................................. 55

      2.2.1.2  Military aviation .................................................... 56
2.2.1.3 Business aviation ............................................................................................ 56
2.2.1.4 General aviation ............................................................................................. 56
2.2.1.5 Unmanned Aerial vehicles (UAVs) .................................................................. 56
2.2.2 Airport system .................................................................................................. 57
2.2.3 Air Navigation Service Providers (ANSPs) ..................................................... 57
   2.2.3.1 Airspace organisation and phases of flight .................................................... 58
2.2.4 Regulators ......................................................................................................... 61
2.3 Current ATM System .......................................................................................... 62
   2.3.1 Air Traffic Services (ATS) ............................................................................... 64
      2.3.1.1 Air Traffic Control ......................................................................................... 64
      2.3.1.2 Support technologies: CNS system ............................................................... 65
   2.3.2 Air Traffic Flow & Capacity Management (ATFCM) function ...................... 67
   2.3.3 Airspace Management (ASM) ......................................................................... 68
   2.3.4 Long-term planning ........................................................................................ 71
   2.3.5 The ATM invariant processes ......................................................................... 72
      2.3.5.1 Prediction ....................................................................................................... 74
      2.3.5.2 Detection ........................................................................................................ 74
      2.3.5.3 Resolution ..................................................................................................... 74
      2.3.5.4 Communication & information management ................................................. 74
   2.3.6 The ATM roles ................................................................................................ 75
      2.3.6.1 The Air Traffic Controller .............................................................................. 75
3.1 En-Route Airspace Capacity Definition ............................................................... 100

3.2 Identification of Airspace Capacity Drivers ......................................................... 102

3.2.1 Literature Review .......................................................................................... 104

3.2.2 United Kingdom’s Civil Aviation Authority Sector Overload Reports ............. 105

3.2.2.1 Overload reports capacity factors ............................................................ 106

3.2.3 Subject Matter Expert discussions ............................................................... 109

3.3 Spatio-Geometrical Limitations: Theoretical Capacity .................................... 112

3.3.1 Separation standards ..................................................................................... 112

3.3.1.1 Navigation performance ......................................................................... 113

3.3.1.2 ATC capabilities ..................................................................................... 115

3.3.1.3 Aircraft exposure .................................................................................... 116

3.3.2 Airspace user preferences .......................................................................... 116

3.3.3 Airspace availability ..................................................................................... 119

3.3.4 Maximum spatio-geometrical capacity: The circle packing problem .......... 119

3.4 Air Traffic Controller Workload .......................................................................... 124

3.4.1 Objective complexity .................................................................................... 126

3.4.1.1 Air traffic complexity ............................................................................. 127

3.4.1.2 Structural complexity .......................................................................... 129

3.4.1.3 System complexity ................................................................................. 130

3.4.2 ATCO cognitive processes ........................................................................... 131
3.4.2.1 Information acquisition and analysis............................................................ 131
3.4.2.2 Decision and action selection................................................................. 133
3.4.2.3 Action execution ..................................................................................... 136
3.5 ASM and ATFCM Functions Performance: Predictability Limitations.............. 136
3.6 Cost-efficiency Limitations ......................................................................... 137
3.7 Automation Workload .................................................................................. 138
3.8 Other Factors ................................................................................................. 139
3.9 Summary ........................................................................................................ 140

CHAPTER 4 Review of Current Airspace Capacity Estimation Methods ............... 143

4.1 The Importance of Airspace Capacity Estimation.......................................... 143
4.2 Methods Focused on Workload Modelling .................................................... 144

4.2.1 Fast Time Simulation (FTS)....................................................................... 146

4.2.1.1 Traffic generation.................................................................................. 147
4.2.1.2 Human performance modelling......................................................... 147
4.2.1.3 Capacity estimation for Fast Time Simulation methods ....................... 155

4.2.2 Real Time Simulation (RTS)..................................................................... 155

4.2.2.1 Performance-based measurements ................................................... 156
4.2.2.2 Subjective estimations....................................................................... 157
4.2.2.3 Physiological measures.................................................................... 159

4.2.3 Replication without simulation ................................................................. 159
5.1.1 The planning process and Airspace Management ........................................ 180

5.2 A Methodology to Estimate ACC Cost-Efficiency ......................................... 181

5.2.1 Calculation of the ACC planning accuracy ............................................... 182

5.2.1.1 The ACC planning process ................................................................. 183

5.2.1.2 Sector Opening Times ................................................................. 183

5.2.1.3 Operational Roster Time ............................................................. 184

5.2.1.4 Airspace Planning Efficiency .......................................................... 186

5.2.1.5 Operations Roster Time Buffer ....................................................... 187

5.2.1.6 Planning Refinement Ratio .............................................................. 187

5.2.1.7 Pre-Tactical Planning Efficiency .................................................... 187

5.2.1.8 Overall Planning Efficiency ............................................................ 188

5.2.2 Airspace Management execution performance assessment ...................... 189

5.2.2.1 Over-deliveries ........................................................................... 194

5.2.2.2 Staffing shortages ......................................................................... 195

5.2.2.3 Utilisation ..................................................................................... 196

5.2.2.4 Sector traffic imbalance ............................................................... 196

5.2.2.5 Airspace Management execution performance calculation ........... 197

5.2.3 Overall Cost-Efficiency ......................................................................... 199

5.3 MUAC Case Study .................................................................................... 200

5.3.1 Planning process evolution accuracy assessment .................................... 205

5.3.2 AEP assessment .................................................................................. 217
CHAPTER 8  Development of a Workload Estimation Methodology

8.1 Proposed Workload Estimation Methodology

8.2 Data Generation

8.2.1 Data pre-processing

8.3 Strategy Identification

8.4 Perceived Complexity Calculation

8.4.1 Occupancy rule

8.4.2 Heading and Direct-to-Point rules

8.4.3 Speed rule

8.4.4 Cleared Flight Level rules

8.5 Mental Workload Estimation

8.6 Calibration

8.6.1 Observations and discussions

8.6.2 Workload reconstruction interviews

8.6.3 MUAC DECO sectors group calibration results

8.7 Summary

CHAPTER 9  Validation and Application of the Workload Estimation Methodology

9.1 Validation Strategy

9.1.1 Step 1: Validation scenarios identification
9.1.2 Step 2: Selection of optimal validation scenarios ........................................340
9.1.3 Step 3: Workload estimation .....................................................................341
9.1.4 Step 4: ATCOs selection ...........................................................................341
9.1.5 Step 5: Workload reconstruction ............................................................342
  9.1.5.1 Sub-step 5.1: Session briefing .............................................................343
  9.1.5.2 Sub-step 5.2: Individual validation scenario briefing ........................344
  9.1.5.3 Sub-step 5.3: Validation scenario replay and workload reconstruction ..345
  9.1.5.4 Sub-step 5.4: Session debriefing .........................................................348
9.1.6 Step 6: Deviation analysis ........................................................................348
9.2 MUAC Validation ..........................................................................................349
  9.2.1 Deviation analysis ....................................................................................353
  9.2.2 Debriefing results ..................................................................................365
9.3 GUAC Validation ..........................................................................................366
9.4 Workload Estimation Methodology Applications ..........................................370
  9.4.1 Real Time Simulation exercises ..............................................................371
  9.4.2 Real-Time operations .............................................................................373
9.5 Summary ........................................................................................................374

CHAPTER 10 Framework Implementation and Interdependencies ..................376
10.1 Airspace Capacity Estimation Framework Implementation ........................376
  10.1.1 Step 1: Input .........................................................................................377
10.1.2 Step 2: Input evaluation .................................................................................. 378

10.1.3 Step 3 - 4: Application of framework areas and analysis of capacity impact 380

10.2 Interdependencies .................................................................................................... 380

10.2.1 Cost-efficiency – Workload ........................................................................... 382

10.2.2 Workload – Predictability (ASM/ATFCM) ................................................... 383

10.2.3 Predictability (ASM/ATFCM) – Cost-efficiency .......................................... 384

10.3 Summary .................................................................................................................. 385

CHAPTER 11 Conclusions and recommendations for future work ......................... 387

11.1 Revisiting Research Objectives ............................................................................... 387

11.2 Main achievements .................................................................................................. 388

11.3 Future work .............................................................................................................. 389

11.3.1 Enhancement of workload estimation methodology ......................................... 390

11.3.2 Modelling of framework areas interdependencies ............................................ 391

11.3.3 Quantification of the cost-efficiency buffer ..................................................... 392

11.4 Publications ............................................................................................................. 393

11.5 Awards ..................................................................................................................... 394

11.6 Patent applications ................................................................................................... 394

References .................................................................................................................... 396

Appendix 1 ...................................................................................................................... 426
LIST OF FIGURES

Figure 1-1 Air traffic evolution in Europe (PRC, 2014) .......................................................... 44

Figure 1-2 Thesis structure .................................................................................................... 47

Figure 1-3 Thesis flow diagram............................................................................................ 49

Figure 2-1 – Controlled airspace configuration ................................................................. 60

Figure 2-2 Phases of flight and control centres (Nolan, 1990) .............................................. 60

Figure 2-3 – ATM services (ICAO, 2007) ................................................................. 63

Figure 2-4 Maximum occupancy as a function of open operational sectors for MUAC sectors groups ......................................................................................................................... 70

Figure 2-5 – The annual capacity planning process (EUROCONTROL, 2007) ................. 72

Figure 2-6 ATM invariant processes .................................................................................. 73

Figure 2-7 Relationships between the different ATM roles (based on MUAC operations) .... 83

Figure 2-8 Time-frames, roles and functions mapping ....................................................... 85

Figure 2-9 ATCO-pilot communications flow ................................................................. 86

Figure 2-10 From the current ATM system to the ATM target concept (SESAR) (adapted from (Schuster and Ochieng, 2010)) ........................................................................................ 91

Figure 2-11 The SESAR shift in the time-frames, roles and functions .............................. 96

Figure 2-12 System Wide Information Management (SWIM) (SESAR, 2007b) ................. 97

Figure 3-1 Template analysis for airspace capacity factors identification .................. 103
Figure 3-2 Separation standards around an aircraft ............................................................... 113

Figure 3-3 Lateral separation minima standards as a function of navigation accuracy........ 115

Figure 3-4 Daily traffic evolution for ESRA flights (data extracted from EUROCONTROL STATFOR portal) .................................................................................................................. 117

Figure 3-5 Daily traffic evolution (weekly focus) ................................................................. 118

Figure 3-6 Munich movements for a typical day (image extracted from (Kösters, 2007) p.22) ................................................................................................................................................ 118

Figure 3-7 Hexagonal circles lattice (Fukshansky, 2011) ..................................................... 120

Figure 3-8 Relationship between sector area and traffic density in MUAC lower sectors.... 124

Figure 3-9 ATCO cognitive memories .................................................................................. 133

Figure 3-10 Workload and cognitive stages ........................................................................... 134

Figure 3-11 Qualitative relationship between the control mode chosen and the workload and traffic planning anticipation ................................................................................................... 136

Figure 4-1 Types of workload estimation methods ............................................................... 146

Figure 4-2 AENA’s RAMS-MWM simulation platform (Boogaard, 2007) ......................... 154

Figure 4-3 Influence diagram (Simonsson, 2011) ................................................................. 163

Figure 4-4 IPL and maximum IPL for each modelled component in Integra methodology (Hudgell and Gingell, 2000) .................................................................................................. 166

Figure 4-5 MAEVA process with the suggested route map highlighted with blue arrow (Revuelta, 2004) ..................................................................................................................... 167

Figure 4-6 Airspace capacity estimation framework .................................................................... 173
Figure 5-1 Airspace capacity estimation framework (focus of this chapter highlighted in blue) ................................................................. 178

Figure 5-2 Cost-efficiency as a function of the number of sectors for MUAC Brussels sector group ................................................................................................................................................ 190

Figure 5-3 AEP polygon ................................................................................................................................................ 198

Figure 5-4 Computation of the OCE metric ........................................................................................................ 199

Figure 5-5 MUAC planning process (Tobaruela et al., 2013) ........................................................................................................ 202

Figure 5-6 PPE evolution ............................................................................................................................................... 208

Figure 5-7 PRR evolution ............................................................................................................................................... 210

Figure 5-8 APE evolution ............................................................................................................................................... 211

Figure 5-9 $\Delta_{ORT}$ evolution ........................................................................................................................................ 213

Figure 5-10 OPE evolution .............................................................................................................................................. 216

Figure 5-11 AEP and its four functional metrics ............................................................................................................ 217

Figure 5-12 Comparison of executed SOT executed / traffic ratio for weekends and weekdays in the MUAC Brussels sectors group ........................................................................................................ 218

Figure 5-13 OCE and its two functional metrics .............................................................................................................. 221

Figure 5-14 GUAC delays per regulation type (where CB indicates weather impact due to CumulunimBus) ........................................................................................................................................ 225

Figure 5-15 Comparison of the OPE distributions for non-zero and zero staffing delay days ................................................................................................................................................ 226

Figure 5-16 The relationship between OPE and staffing delays for days with non-zero staffing delays ........................................................................................................................................... 227
Figure 5-17 Density plot for GUAC OPE................................................................. 228
Figure 5-18 Fit of the probability data within the 1-standard deviation interval........ 229
Figure 5-19 MUAC Brussels vs. GUAC OPE.............................................................. 232
Figure 6-1 Airspace capacity estimation framework (focus of this chapter highlighted in blue) ................................................................................................................................................ 239
Figure 6-2 Predictability framework architecture...................................................... 249
Figure 6-3 MUAC ARTAS positioning error.............................................................. 250
Figure 6-4 EFD temporal error for all flights on 07/02/13 ......................................... 254
Figure 6-5 Original trajectory error evolution (left) and trajectory error evolution after associating a unique error for each one-minute LAT interval ............................................. 255
Figure 6-6 Mean and standard deviation temporal error evolution ......................... 256
Figure 6-7 Temporal error evolution for predictions using flight plan information (flights still on ground) and radar track positioning reports (airborne flights)................................. 257
Figure 6-8 Flights distribution according to the absolute error for Brussels East High (left) and Brussels East Low (right)..................................................................................................... 259
Figure 6-9 Comparison of NM and PhD module framework occupancy................... 260
Figure 6-10 Trajectory of a flight closed to sector boundaries. Red line corresponds to the airway whilst the blue line corresponds to the flown trajectory................................. 261
Figure 6-11 Actual (LAT=0) and predicted occupancy (LAT>0) during a period of the day for different LATs..................................................................................................................... 263
Figure 6-12 Example of occupancy error (y-axis) as a function of the LAT (x-axis). Snapshot made at 08:32 UTC for EGLL departures (blue) and the rest of the traffic (green).......... 264
Figure 6-13 Flight plan activation effect on the occupancy error .......................................... 265

Figure 6-14 Flow diagram of the hypothetical framework module ........................................ 266

Figure 6-15 Original (red line) and new (blue line) temporal error accuracy. ...................... 270

Figure 6-16 Relationships between the predictability framework Matlab functions ............. 272

Figure 6-17 Ratio of airborne flights as function of LAT for the MUAC airspace ............... 276

Figure 7-1 Airspace capacity estimation framework (focus of this chapter highlighted in blue) ................................................................................................................................................ 278

Figure 7-2 – Time-frames of the DPI messages (adapted from (Koolen, 2012)) ............... 280

Figure 7-3 Data sets and scenarios for performance evaluation ............................................ 281

Figure 7-4 – ADI temporal prediction error evolution (continuous line – average; dashed line – standard deviation) .............................................................................................................. 283

Figure 7-5 – EDI temporal prediction error evolution (continuous line – average; dashed line – standard deviation) .............................................................................................................. 284

Figure 7-6 – ADI occupancy prediction error for the original, baseline and hypothetical scenarios in the MUAC DECO sectors ................................................................. 286

Figure 7-7 – Evaluation of different $\sigma_{\text{Error}}$ on the occupancy prediction error performance .287

Figure 7-8 – EDI occupancy prediction error evolution for the original, baseline and hypothetical scenarios in the MUAC DECO sectors ................................................................. 288

Figure 7-9 – Effect of large delays on EHAM airport departures ........................................ 291

Figure 7-10 Occupancy error distribution ............................................................................ 300

Figure 7-11 Predictability buffer (measured as occupancy) as a function of the PR ratio .... 301
Figure 7-12 All Thursdays in summer 2013 MUAC DELTA sector occupancy prediction error (continuous line – average; dashed line – standard deviation) ..............................................302

Figure 7-13 Occupancy predictability error comparison for large (blue) and small (red) operational sectors (continuous line show mean values and dashed lines standard deviations) ................................................................................................................................................303

Figure 8-1 Airspace capacity estimation framework (focus of this chapter highlighted in blue) ................................................................................................................................................306

Figure 8-2 Workload and cognitive stages (Section 3.4) ............................................................................308

Figure 8-3 Workload estimation methodology (Tobaruela et al., 2014b) .............................................310

Figure 8-4 Example of strategy identification in the vertical dimension .............................................317

Figure 8-5 Example of strategy identification in the lateral dimension ..............................................318

Figure 8-6 Workload reconstruction interview process ........................................................................328

Figure 9-1 Airspace capacity estimation framework (focus of this chapter highlighted in blue) ................................................................................................................................................336

Figure 9-2 Validation strategy flow diagram .........................................................................................338

Figure 9-3 Validation session flow (time in minutes) ..............................................................................343

Figure 9-4 Workload reconstruction set-up ..........................................................................................346

Figure 9-5 Workload scale prompt in the workload assessment tablet ..............................................347

Figure 9-6 Frequency of responses per workload level and ATCO ..................................................353

Figure 9-7 Real-time workload monitoring (Tobaruela et al., 2014b) ..................................................374

Figure 10-1 Airspace capacity estimation framework ............................................................................377
Figure 10-2 Relationships between operational improvement categories and framework areas
................................................................................................................................................ 378

Figure 10-3 Interdependencies between framework areas..................................................... 381

Figure 11-1 Airspace capacity estimation framework ........................................................... 387
LIST OF TABLES

Table 2-1 ATM system evolution ........................................................................................................... 54
Table 2-2 – Processes and roles mapping ............................................................................................. 73
Table 2-3 ATCO goals ............................................................................................................................ 76
Table 2-4 Levels of automation of decision and action selection (Parasuraman et al., 2000). 81
Table 3-1 Literature review of airspace capacity factors .................................................................... 104
Table 3-2 Dedicated sector overload template ...................................................................................... 107
Table 3-3 Sector overload factors histogram ....................................................................................... 108
Table 3-4 RNP classification (ICAO, 1999) ......................................................................................... 114
Table 3-5 Relationship between RNP and lateral separation minima ............................................. 114
Table 3-6 Calculation of actual traffic densities and theoretical capacities in MUAC airspace sectors ............................................................................................................................. 122
Table 3-7 Air traffic pattern complexity factors .................................................................................... 128
Table 4-1 Use of FTS tools of interviewed countries ......................................................................... 150
Table 4-2 Qualitative comparison of capacity estimation techniques .............................................. 172
Table 4-3 Airspace capacity estimation framework areas and chapters organisation .............. 175
Table 5-1 MUAC major planning process related improvements ....................................................... 205
Table 5-2 MUAC major events since 2009 ......................................................................................... 206
Table 5-3 PPE evolution descriptive statistics ..................................................................................... 209
Table 5-4 PRR evolution descriptive statistics

Table 5-5 APE descriptive statistics

Table 5-6 Overstaffing evolution in MUAC measured in ATCOs/flight

Table 5-7 $\mu \Delta ORT$ for summer and winter periods (before transition values highlighted in grey)

Table 5-8 OPE and planning process inefficiencies for summer and winter periods (prior to transition values are highlighted in grey)

Table 5-9 Over-deliveries average values

Table 5-10 Utilisation average values

Table 5-11 Linear correlation coefficients (p<0.01 except*)

Table 5-12 Fit parameters of the probability functional relationship

Table 5-13 Comparison of summer and winter OPE average values

Table 5-14 – SESAR OI step definition (SESAR, 2014). * Operational Focus Area (OFA); Initial Operating Capability (IOC); Full Operating Capability (FOC)

Table 5-15 – SESAR OI steps definitions (SESAR, 2014)

Table 5-16 – SESAR OI steps definitions associated with the business trajectory concept (SESAR, 2014)

Table 5-17 – SESAR OI step definition (SESAR, 2014)

Table 5-18 – SESAR OI step definition (SESAR, 2014)

Table 5-19 – SESAR OI step definition (SESAR, 2014)

Table 6-1 ETFMS flight progress messages
Table 6-2 ARTAS flight track example

Table 6-3 EFD predictions example

Table 6-4 Absolute error distribution at LAT=60 mins for Brussels East High and Low sectors

Table 6-5 Example of an actual trajectory close to sector boundaries

Table 6-6 EFD re-computation example

Table 6-7 Example of hypothetical scenario parameters

Table 7-1 DPI messages frequency

Table 7-2 – Statistical characterisation and normal approximations of ADI and EDI messages

Table 7-3 – List of SESAR OIs with enhanced ground information sharing processes

Table 7-4 – List of SESAR OIs with enhanced trajectory information sharing processes

Table 7-5 – List of SESAR OISs introducing new air traffic operations leading to enhanced predictability

Table 8-1 MUAC input types and definition

Table 8-2 Input log example

Table 8-3 Flight level log example

Table 8-4 Inputs sequence for the two scenarios in Figure 8-4

Table 8-5 Inputs sequence for the two scenarios in Figure 8-5

Table 8-6 Relationship between perceived complexity and qualitative workload level (Tobaruela et al., 2014b)
Table 8-7 Example of methodology break-down .................................................................329

Table 8-8 MUAC DECO sectors group logic rules and complexity vectors calibration......334

Table 9-1 Workload levels and associated definitions ..........................................................347

Table 9-2 Validation scenarios .........................................................................................350

Table 9-3 Validation scenarios characterization ................................................................350

Table 9-4 Characterisation of the ATCOs validation team ................................................351

Table 9-5 Percentage of workload level responses.............................................................353

Table 9-6 Workload ratings and methodology outputs in validation scenario 1 ...............355

Table 9-7 Workload ratings and methodology outputs in validation scenario 2 ...............356

Table 9-8 Workload ratings and methodology outputs in validation scenario 3 ...............357

Table 9-9 Workload ratings and methodology outputs in validation scenario 4 ...............358

Table 9-10 Workload ratings and methodology outputs in validation scenario 5 ..........359

Table 9-11 Workload ratings and methodology outputs in validation scenario 6 ..........360

Table 9-12 Absolute accuracy of workload estimation methodology outputs ................362

Table 9-13 ATCOs ratings and methodology Spearman’s rank coefficient.......................363

Table 9-14 Workload validation findings .........................................................................364

Table 9-15 Debriefing questionnaire results (1-strongly disagree; 2-disagree; 3-agree; 4-strongly agree) ................................................................................................................365

Table 9-16 Correspondence between MUAC and GUAC ATCO clearances .................367

Table 9-17 GUAC logic rules and complexity vectors calibration.....................................369
Table 9-18 – List of SESAR OISs aiming ATCO workload reductions ...............................372

Table 11-1 Data usage type for the different ACCs and chapters .................................388

Table 11-2 Main achievements and impacts..................................................................389
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4D</td>
<td>Four-Dimensional</td>
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<tr>
<td>(\alpha)</td>
<td>Significance level</td>
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<tr>
<td>(\mu)</td>
<td>Mean</td>
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<tr>
<td>(\sigma)</td>
<td>Standard deviation</td>
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<tr>
<td>ACC</td>
<td>Area Control Centre</td>
</tr>
<tr>
<td>A-CDM</td>
<td>Airport-Collaborative Decision Making</td>
</tr>
<tr>
<td>ACES</td>
<td>Advanced Concepts Evaluation System</td>
</tr>
<tr>
<td>ADD</td>
<td>Aircraft Derived Data</td>
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<td>Airport of DEParture</td>
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<td>ATFCM</td>
<td>Air Traffic Flow &amp; Capacity Management</td>
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<td>ATM</td>
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<td>ATOT</td>
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<td>ATS</td>
<td>Air Traffic Service</td>
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<td>ATSU</td>
<td>Air Traffic Service Unit</td>
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<td>BADA</td>
<td>Base of Aircraft DAta</td>
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<td>BDT</td>
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<tr>
<td>CAPAN</td>
<td>CApacity ANalyser</td>
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<td>CASA</td>
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<tr>
<td>CB</td>
<td>CumuluNimbus</td>
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<tr>
<td>CDM</td>
<td>Collaborative Decision Making</td>
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<tr>
<td>C-DPI</td>
<td>Cancel – DPI message</td>
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<tr>
<td>CDR</td>
<td>ConDitional Route</td>
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<td>Cleared Flight Level</td>
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<td>Central Flow Management Unit</td>
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<td>CHMI</td>
<td>Central flow management unit Human-Machine Interface</td>
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<td>CIM</td>
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<tr>
<td>CNS</td>
<td>Communication, Navigation and Surveillance</td>
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<td>CPDLC</td>
<td>Controller-Pilot Data Link</td>
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<td>Correlated Position Report message</td>
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<td>CS</td>
<td>Call Sign</td>
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<td>CSS</td>
<td>Central Supervisory Section</td>
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<td>CTA</td>
<td>Controlled Time of Arrival</td>
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<td>Calculated Take-Off Time</td>
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<tr>
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<td>ConTRol zone</td>
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<td>D2P</td>
<td>Direct-to-Point</td>
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<td>dDCB</td>
<td>dynamic Demand &amp; Capacity Balancing</td>
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<td>DElta-COastal</td>
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<td>DOP</td>
<td>Daily Operations Plan</td>
</tr>
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<td>DPI</td>
<td>Departure Planning Information message</td>
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<td>DST</td>
<td>Decision Support Tool</td>
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<td>EASA</td>
<td>European Aviation Safety Agency</td>
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<td>Abbreviation</td>
<td>Description</td>
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<td>Executive Controller</td>
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<td>EDI</td>
<td>Early – DPI</td>
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<td>EFD</td>
<td>ETFMS Flight Data</td>
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<td>Executive Operations Support</td>
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<td>Eurocontrol Statistical Reference Area</td>
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<td>Entry Time</td>
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<td>FAB</td>
<td>Functional Airspace Block</td>
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<td>FANS</td>
<td>Future Air Navigation Systems</td>
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<td>FCFS</td>
<td>First-Come-First-Served</td>
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<tr>
<td>FDPS</td>
<td>Flight Data Processing System</td>
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<td>FID</td>
<td>Flight IDentification</td>
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<td>FIR</td>
<td>Flight Information Region</td>
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<td>FIS</td>
<td>Flight Information Services</td>
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<td>FL</td>
<td>Flight Level</td>
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<td>FMP</td>
<td>Flow Management Position operator</td>
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<td>FMS</td>
<td>Flight Management System</td>
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<td>FTS</td>
<td>Fast Time Simulation</td>
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<td>FSA</td>
<td>First System Activation message</td>
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<td>FUA</td>
<td>Flexible Use of Airspace</td>
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<td>Geneva Upper Area Control</td>
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<td>Heading</td>
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<td>HITL</td>
<td>Human-In-The-Loop</td>
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<td>ICAO</td>
<td>International Civil Aviation Organization</td>
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<td>IFP</td>
<td>Initial Flight Plan message</td>
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<td>IFR</td>
<td>Instrument Flight Rules</td>
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<td>ILS</td>
<td>Instrument Landing System</td>
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<td>IMC</td>
<td>Instrument Meteorological Conditions</td>
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<td>INS</td>
<td>Inertial Navigation System</td>
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38
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<td>Information Processing Load</td>
</tr>
<tr>
<td>IPL</td>
<td>Instantaneous Self-Assessment</td>
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<tr>
<td>ISA</td>
<td>Kilo Hertz</td>
</tr>
<tr>
<td>KPA</td>
<td>Key Performance Area</td>
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<td>KPI</td>
<td>Key Performance Indicator</td>
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<td>LACC</td>
<td>London Area Control Centre</td>
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<td>LARA</td>
<td>Local and Regional ASM Application</td>
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<td>LAT</td>
<td>Look-Ahead Time</td>
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<td>LoA</td>
<td>Letter of Agreement</td>
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<td>LOS</td>
<td>Loss Of Separation</td>
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<td>MACE</td>
<td>MALvern Capacity Estimate</td>
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<td>MAP</td>
<td>Monitor Alert Parameter</td>
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<tr>
<td>MHz</td>
<td>Mega Hertz</td>
</tr>
<tr>
<td>MNPS</td>
<td>Minimum Navigation Performance Specification</td>
</tr>
<tr>
<td>MOR</td>
<td>Mandatory Occurrence Reporting</td>
</tr>
<tr>
<td>MRT</td>
<td>Multiple Resources Theory</td>
</tr>
<tr>
<td>MSAW</td>
<td>Minimum Safe Altitude Warning</td>
</tr>
<tr>
<td>MSP</td>
<td>Multi Sector Planner</td>
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<td>MTCID</td>
<td>Medium-Term Conflict Detection</td>
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<td>MUAC</td>
<td>Maastricht Upper Area Control</td>
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<td>MWM</td>
<td>Multi-Workload Model</td>
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<td>NAA</td>
<td>National Aviation Authority</td>
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<td>NASA-TLX</td>
<td>NASA Task Load Index</td>
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<td>NDB</td>
<td>Non-Directional Beacon</td>
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<td>N-FDPS</td>
<td>New-Flight Data Processing System</td>
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<td>NFL</td>
<td>eNtry Flight Level</td>
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<td>NM</td>
<td>Network Manager</td>
</tr>
<tr>
<td>Nm</td>
<td>Nautical mile</td>
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<tr>
<td>OACC</td>
<td>Oceanic Area Control Centre</td>
</tr>
<tr>
<td>OCE</td>
<td>Overall Cost-Efficiency</td>
</tr>
<tr>
<td>OFA</td>
<td>Operational Focus Area</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>OI</td>
<td>Operational Improvement</td>
</tr>
<tr>
<td>OIS</td>
<td>Operational Improvement Step</td>
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<tr>
<td>OPE</td>
<td>Overall Planning Efficiency</td>
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<tr>
<td>ORT</td>
<td>Operational Roster Time</td>
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<tr>
<td>OTMV</td>
<td>Occupancy Traffic Monitoring Value</td>
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<tr>
<td>p</td>
<td>Statistical significance</td>
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<tr>
<td>PC</td>
<td>Planning Controller</td>
</tr>
<tr>
<td>pETI</td>
<td>predicted ETI</td>
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<tr>
<td>PPE</td>
<td>Pre-tactical Planning Efficiency</td>
</tr>
<tr>
<td>PR</td>
<td>Prediction Reliability</td>
</tr>
<tr>
<td>PRR</td>
<td>Planning Refinement Ratio</td>
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<tr>
<td>PSR</td>
<td>Primary Surveillance Radar</td>
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<tr>
<td>pTime</td>
<td>prediction Time</td>
</tr>
<tr>
<td>pTOT</td>
<td>predicted TOT</td>
</tr>
<tr>
<td>PUMA</td>
<td>Performance and Usability Modelling in ATM</td>
</tr>
<tr>
<td>pXTI</td>
<td>predicted XTI</td>
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<tr>
<td>radar</td>
<td>RAdio Detection And Ranging</td>
</tr>
<tr>
<td>RAMS</td>
<td>Reorganized ATC Mathematical Simulator</td>
</tr>
<tr>
<td>RBT</td>
<td>Reference Business Trajectory</td>
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<tr>
<td>RIMCAS</td>
<td>Runway Incursion Monitoring and Collision Avoidance System</td>
</tr>
<tr>
<td>RNP</td>
<td>Required Navigation Performance</td>
</tr>
<tr>
<td>RTS</td>
<td>Real Time Simulation</td>
</tr>
<tr>
<td>RVSM</td>
<td>Reduced Vertical Separation Minima</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research &amp; Development</td>
</tr>
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<td>SBT</td>
<td>Shared Business Trajectory</td>
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<td>SES</td>
<td>Single European Sky</td>
</tr>
<tr>
<td>SESAR</td>
<td>Single European Sky ATM Research</td>
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<td>SME</td>
<td>Subject Matter Expert</td>
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<td>SOT</td>
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<td>SPD</td>
<td>SPeeD</td>
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<td>SPT</td>
<td>Statistical Prediction Tool</td>
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<td>SSR</td>
<td>Secondary Surveillance Radar</td>
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<td>Acronym</td>
<td>Description</td>
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<td>STCA</td>
<td>Short-Term Conflict Avoidance</td>
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<td>SWAT</td>
<td>Subjective Workload Assessment Technique</td>
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<td>System Wide Information Management</td>
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<td>TAAM</td>
<td>Total Airspace and Airport Modeller</td>
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<td>TBO</td>
<td>Trajectory-Based Operation</td>
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<td>The Traffic Collision Avoidance System</td>
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<td>Target – DPI</td>
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<td>TFL</td>
<td>Transfer Flight Level</td>
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<td>TMA</td>
<td>Terminal Manoeuvring Area</td>
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<td>TMR</td>
<td>Trajectory Management Requirements</td>
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<td>Traffic Monitoring Value</td>
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<td>Top Of Descent</td>
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<tr>
<td>TOT</td>
<td>Take-Off Time</td>
</tr>
<tr>
<td>TP</td>
<td>Trajectory Prediction</td>
</tr>
<tr>
<td>TSA</td>
<td>Target StArt-up – DPI</td>
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<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
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<tr>
<td>US</td>
<td>United States of America</td>
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<tr>
<td>VAMS</td>
<td>Virtual Airspace Modeling and Simulation</td>
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<td>Visual Flight Rules</td>
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<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>VMC</td>
<td>Visual Meteorological Conditions</td>
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<tr>
<td>VOR</td>
<td>VHF Omnidirectional Range</td>
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<tr>
<td>XTI</td>
<td>eXit Time</td>
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CHAPTER 1  INTRODUCTION

The objective of this chapter is to set the scene for the research presented in this PhD thesis. It introduces the background to the research, outlining the basic principles of the air transport system and its components, including the Air Traffic Management (ATM) system and the importance of airspace capacity estimation (Section 1.1). Based on this background, the research objectives are defined and a methodology is outlined to accomplish these objectives (Section 1.2). The final section describes the thesis structure, including the objectives of individual chapters and their interrelationships (Section 1.3).

1.1 Background

Since the first flight on December 17, 1903, aviation has rapidly evolved, and become a key element in the worldwide economy. Currently, the air transport industry is a widely used indicator of economic wealth and growth, with studies showing the high correlation between the population income and the levels of air mobility of such population (Schafer and Victor, 2000). Therefore, the air transport industry plays a vital role in the economy of the states, maintaining and stimulating economic growth and social development, including the generation of employment, wealth, stimulation of tourism and facilitation of worldwide commerce.

In Europe’s recent history, air traffic demand has increased at a rapid rate (Figure 1-1) except for the periods around 2001 and 2009 due to the terrorist attacks on 11 September and the global economic crisis respectively. The impacts of the global recession mean that Instrument Flight Rule (IFR) flights will not reach the levels seen in 2008 until 2016, Long-term (starting in 2008) projections of air traffic suggest that in 2035 there will be 1.5 times the number of flights in 2012 and rising to double the number of IFR flights in 2050 compared to 2012 (EUROCONTROL, 2013).
The aim of the air transport system is to enable the transport of payload (commercial aviation) or the accomplishment of a mission (military and general aviation), through the operation of aircraft. The air transport system is the result of the interaction of several individual components that enable the accomplishment of this objective. The main components constituting the air transport system are the aircraft, the airspace users (e.g. the commercial airlines) and the ATM system (Hansman, 2005, SESAR, 2006, Sipe and Moore, 2009).

The basic working principle of the air transport system is that as soon as air traffic demand exists, airspace users plan flights to accommodate that demand or accomplish the mission objectives, making optimal use of their resources (aircraft, flight crew or ground vehicle amongst others). Hours before and during the flight execution, the ATM system enables the airspace users to fly their desired flight profiles, including arrival and destination times, ensuring the separation of all the air traffic (ICAO, 2002).

Today’s air traffic operations in the densest airspaces, including the European core area, are already facing a number of issues, including inefficiencies such as delays due to traffic congestion (EUROCONTROL, 2011). In a status-quo scenario, these inefficiencies are
expected to become even more pronounced in the future due to the significantly higher anticipated traffic. The source of these inefficiencies is a fundamentally saturated air navigation system that is unable to accommodate the air traffic demand to within the required standards of safety, efficiency and environmental sustainability.

In order to enhance performance, worldwide initiatives are being deployed to guide the modernisation of the air transport industry through enhanced operations supported by technical advances. The Single European Sky through its implementation program the Single European Sky ATM Research (SESAR) is in charge of delivering this transformation at a European level.

One of the main concerns that these modernisation initiatives have raised is their feasibility to achieve the declared capacity targets at the same time as ensuring adequate levels of cost-effectiveness, environmental impact and safety.

Current airspace capacity estimation methods are fundamentally focused on quantifying Air Traffic Controller (ATCO) workload as this is the most significant airspace capacity driver. However, other factors of growing importance will significantly limit airspace capacity in a more automated ATM system, especially those related to the performance of the Airspace Management (ASM) and Air Traffic Flow and Capacity Management (ATFCM) functions. In order to accurately estimate airspace capacity it is necessary to capture the effect of these additional factors.

1.2 Aims and Objectives

The overall aim of this thesis is to develop a framework that assesses the impact of ATM modernisation initiatives on airspace capacity.

This main aim is supported by the following objectives:

1. The identification of airspace capacity factors based on critical literature review and discussions with Subject Matter Experts (SMEs).
2. The modelling of these factors.
3. Implementation of the framework modelling methodologies in representative Air
Traffic Control (ATC) centres in Europe, contributing towards optimising current performance and assessing the adequacy of future deployment plans.

1.3 Thesis Structure

In order to achieve the research aim and objectives, the thesis is organised in chapters, each making use of a concrete general methodology and with an associated purpose (Figure 1-2).
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>METHODOLOGY</th>
<th>OUTCOMES</th>
</tr>
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<tbody>
<tr>
<td>2. Fundamentals of ATM</td>
<td>Critical review and discussions with SMEs</td>
<td>Characterisation of the ATM system</td>
</tr>
<tr>
<td>3. Airspace Capacity</td>
<td>Critical review and discussions with SMEs</td>
<td>Airspace capacity drivers identification</td>
</tr>
<tr>
<td>4. A Review of Current Airspace Capacity Estimation Methods</td>
<td>Critical review and discussions with SMEs</td>
<td>Classification of methods and critical assessment</td>
</tr>
<tr>
<td>5. The Capacity Cost-Efficiency Trade-Off</td>
<td>Development, application and evaluation of model</td>
<td>ATC centre planning process and capacity/cost-efficiency modelling</td>
</tr>
<tr>
<td>7. Evaluation and Application of the Predictability Framework</td>
<td>Application and mathematical/statistical evaluation of the model</td>
<td>Effects of the lack of predictability on airspace capacity</td>
</tr>
<tr>
<td>9. Validation and Application of the Workload Model</td>
<td>Statistical validation of the model and application</td>
<td>Validation of the workload estimation methodology</td>
</tr>
<tr>
<td>10. Framework Implementation and Interdependencies</td>
<td>Qualitative discussion</td>
<td>Framework implementation and interdependencies between framework areas</td>
</tr>
<tr>
<td>11. Conclusions and Recommendations for Future Work</td>
<td>Findings summary and discussion of the impact</td>
<td>Research impact and guidelines for future work</td>
</tr>
</tbody>
</table>

Figure 1-2 Thesis structure

In Figure 1-2 the fundamental methodologies to achieve each chapter outcome are described.
These methodologies include the following:

- Critical literature review and discussion with Subject Matter Experts (SMEs): This is used during the first stages of the research to ensure a correct understanding of ATM operations and airspace capacity. Instead of relying only on the critical review, discussions were held with SMEs from key ATC centres in Europe including Eurocontrol – Maastricht Upper Area Control (MUAC) centre, Skyguide – Geneva Area Control Centre (ACC) (Switzerland), NATS – Swanwick ACC and Prestwick ACC (United Kingdom), AENA – Madrid ACC (Spain) and ROMATSA – Bucharest ACC (Romania).

- Mathematical development of models: Following the identification of the main airspace capacity drivers, these are modelled. The concrete technique depends upon the nature of the driver and will be identified in each associated chapter.

- Application of the models to specific ATC centres and data sets: Following the theoretical development of the models, these are implemented in real ATC centres. The application of the models requires pre-processing available data sets in the ATC centres and the creation of automated tools that repeatedly generate results at the ATC centre to assess its performance.

- Evaluation and validation of the models: The developed models of the identified capacity drivers are evaluated and validated using operational data. Depending on the nature of the capacity factor being modelled, the validation task will require either the involvement of humans in the validation or simply automatically generated data.

The various thesis chapters are interconnected as shown in the diagram in Figure 1-3. The proposed structure is sequential. Furthermore, due to the inherent nature of each chapter, these can be classified either as introduction, review, development, validation or conclusion.
CHAPTER 1 and CHAPTER 2 constitute the introduction chapters. The former is the current chapter in which the background to the research, aims and objectives and the thesis structure are defined. The latter defines in depth how the air transport system and in particular the ATM system operates in order to examine the implication of the system performance on airspace capacity.

Based on the knowledge acquired in the first two introductory chapters, the research progresses to the review stage in which a revision of past theories and research is carried out in order to identify the airspace capacity problem, its main drivers and the different techniques used to estimate airspace capacity. The results of these findings conclude with a proposed capacity estimation framework, which addresses the deficiencies identified in existing frameworks.

On the basis of the proposed framework, subsequent chapters elaborate models and
methodologies relative to each of the three main framework areas. Each of the corresponding chapters develops a methodology followed by its validation.

The interdependencies and implementation of the developed methodologies of the three framework areas are discussed in CHAPTER 10. CHAPTER 11 concludes with a summary of the main research achievements with respect to the initial research objectives.
CHAPTER 2    FUNDAMENTALS OF AIR TRAFFIC MANAGEMENT

This chapter outlines the fundamentals of ATM for the current and future systems and captures the paradigm shift between them. This provides the basis for understanding the implications on airspace capacity.

Throughout this thesis the current ATM system will be referred to as the one existing in European countries prior to the start of the SESAR deployment period (SESAR, 2008a).

Section 2.1 gives a historical perspective of the evolution of the ATM system from its origins until present. Section 2.2 describes the organisation of the ATM system and its different stakeholders. Section 2.3 details the current ATM system to understand its operations, including processes, functions, roles and timeframes. Especial attention is given to the Airspace Management, Air Traffic Flow & Capacity Management and Air Traffic Control functions as they will be proven to be of key importance in delivering airspace capacity. Given the current ATM system, Section 2.4 identifies the shortcomings of the system and Section 2.5 introduces the European approach to overcome these ATM system inefficiencies.

2.1 Evolution of Air Traffic Management (ATM)

Even though the ATM system has gone through an evolutionary process its main objective has remained invariant: ensure the safety and efficiency of air transport. The ATM system has evolved according to the needs of the aviation industry. In the first days of aviation, the traffic density was sufficiently low so that aircraft could be separated just relying on visual traffic identification accomplished by the pilot. The “keep to the right” rule, coming from ground and maritime means of transport was adopted, and this was sufficient for maintaining aircraft separated (Gilbert, 1973).

Ground separation started to be performed in the decade of 1920 at the airports. Ground controllers made use of visual aids to provide a one-way communication with the pilots. In the 1930’s the introduction of the radio provided a two-way communication channel that
enhanced the separation task carried out by the controllers on the ground (Billings, 1996). Since aircraft position could not be accurately determined, separation was made according to pre-established procedures (procedural separation), where the aircraft position was estimated based on the latest position report provided by the pilot.

After World War I, a number of bombers were converted for mail transport. This augmented the air traffic density although visual separation remained sufficiently safe. In 1919 the International Commission for Air Navigation, a body of the League of Nations, standardised the first set of rules of the air.

Likewise, following World War II, a large number of military aircraft were converted for civilian use, significantly increasing the density of air traffic compared to the pre-World War II era. Furthermore, there major enhancements to aircraft performance (in particular, both their speed and range) in this period. These two factors prevented the safe air operation of aircraft in the busiest areas such as airports and Terminal Manoeuvring Areas (TMAs) without commensurate enhancements to the ATM system.

A further milestone associated with World War II was the introduction of the RAdio Detection And Ranging (radar). The radar was used to detect aircraft and other vehicles through the broadcast of waves that were reflected by the vehicle, and captured by a receiver on the ground. This technology enabled introducing all-weather operations, making the air transport system less reliant on weather conditions. The radar, which was widely deployed during the last years of the 1950’s, produced a change in the way traffic was controlled, from procedural control to the radar control.

Following the introduction of radar, situational awareness was significantly enhanced within the coverage area, over the former procedural control approach, where the position was being estimated based on the latest position report provided by the pilot. This shift resulted in a large reduction in the uncertainty and a subsequent increase in airspace capacity. Air traffic was separated by means of ATCO clearances based on the known position from the aircraft and the estimated future position made by ATCO (clearance-based separation).

During the 1950’s, there was further step change in commercial jet aircraft produced another step change in terms of aircraft performance (Fraser, 1952). This led to the segmentation of
airspace in order to separate fast jet traffic flows from slower aviation. In addition, traffic surveillance and aircraft navigation was improved by the extensive use of ground beacons such as the Very High Frequency (VHF) Omnidirectional Range (VOR). The VOR, which enables positioning the aircraft relative to the ground beacon, significantly increased the navigational accuracy of air traffic and contributed to the creation of a route network.

During the 1960s’, radar evolved into the Secondary Surveillance Radar (SSR), which not only provided the ATCO with position and bearing of aircraft, but also additional information such as identification and altitude.

During the 1970’s and 1980’s, the air transport system experienced a great development with the introduction of large capacity aircraft (e.g. Boeing 747), the supersonic aircraft (i.e. BAC/Aerospatiale Concorde) and the development of large turbofan long-range twin aircraft. These developments fostered the movement of air traffic passengers worldwide, which was closely supported by important enhancements in ground infrastructure to accommodate increasing traffic. An example of these developments was the Instrument Landing System (ILS), which enabled reduced visibility operations by guiding the aircraft during the approach and landing to the runway.

During the 1990’s the Air Traffic Flow Management (ATFM) function was created to tackle the congestion of the network. The ATFM function was not associated with a single technology implementation, but with an overall increased awareness of the state of the network through shared information and prediction tools.

Following the introduction of the SSR, the ATM system has not undergone any major changes: primary radar and SSR remain the fundamental surveillance technologies in ATC. This lack of system development contributes to a number of inefficiencies in the current air transport network (Section 2.4) that need to be addressed. As a result, several modernisation programs based on the International Civil Aviation Organization’s (ICAO) Global ATM Operational Concept (ICAO, 2005b), are in the process of upgrading their ATM systems, with the main objective of moving from radar control to Trajectory-Based Operations (TBOs). TBOs are based on separating aircraft by means of trajectory clearances instead of the current radar-based clearances.
With the introduction of TBOs, a paradigm shift will occur in the ATM system: aircraft separation will occur with more anticipation, fundamentally due to enhanced trajectory prediction tools, enabling trajectory agreements between ATM stakeholders. Compliance of flown trajectories to agreed trajectories will be monitored and a greater accuracy in the future aircraft position will be achieved (Table 2-1).

<table>
<thead>
<tr>
<th>Past System</th>
<th>Current System</th>
<th>Future System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous position</td>
<td>Known</td>
<td>Known</td>
</tr>
<tr>
<td>Current position</td>
<td>Estimated</td>
<td>Known</td>
</tr>
<tr>
<td>Future position</td>
<td>Estimated</td>
<td>Estimated</td>
</tr>
<tr>
<td>Type of separation</td>
<td>Procedural</td>
<td>Clearance-based</td>
</tr>
</tbody>
</table>

This knowledge in the future state of the aircraft will support a more strategic management of air traffic, and this will give an increasingly important role to the functions in charge of the strategic management of air demand i.e. the AirSpace Management (ASM) and Air Traffic Flow & Capacity Management (ATFCM) functions.

### 2.2 Stakeholders of Air Traffic Management

The stakeholders that form the ATM community can be classified in terms of their involvement in ATM operations i.e. operational and non-operational stakeholders (Božičević, 2008). The non-operational stakeholders are those affected by the development of the ATM system activities although they do not directly participate in them. These include stakeholders providing support to enable operations, such as ATM system manufacturers and developers (e.g. communications, navigation systems, surveillance and meteorological information systems), ATCO training centres, technology and Research & Development (R&D) companies and airborne systems manufacturers (ICAO, 2005b).

The operational stakeholders of the ATM system include (ICAO, 2005b): airspace users, aerodrome system, Air Navigation Service Providers (ANSPs) and regulators. These are described in turn in the following sections.
2.2.1 Airspace users

The airspace users can be classified in terms of their business activity into one of the following groups: commercial aviation, military aviation, general aviation, business aviation and Unmanned Aerial Vehicles (UAVs). In optimising operations, airspace users carry out a range of activities, from initial strategic planning of crews and schedules in collaboration with the airport operator, to the execution of the flight, during which the flight crew is responsible for the navigation and guidance of the aircraft.

Airspace users can be classified in terms of their navigation capabilities. Depending on the weather conditions aircraft can operate either under Visual Meteorological Conditions (VMC) or Instrument Meteorological Conditions (IMC). The focus of this thesis are the IFR flights which predominantly operate in the busiest airspace in which capacity constraints typically occur (FAA, 2013).

The sections below introduce each of the groups of airspace users.

2.2.1.1 Commercial aviation

Commercial aviation encompasses all the flights that transport a payload (passenger and/or cargo) to generate profit. The business models of commercial aviation can differ, distinguishing between legacy and low-cost carriers. From an ATM perspective the main difference between these two resides in the business model type: hub & spoke operations from principal airports and point-to-point operations from secondary airports respectively. Moreover, the performance of the aircraft belonging to each group can differ in terms of the desired flight altitude and speed. For instance, low-cost carriers specially emphasise the efficiency of the operation (e.g. low fuel consumption), therefore typically performing slower flight speeds for these flights.

Commercial aviation is the predominant airspace user category in the busiest airspaces where capacity constraints arise, thus the focus will be mainly in this group throughout the thesis.
2.2.1.2 Military aviation

General aviation is essentially all other aviation, excluded from the above categories, including rotorcraft, aerial work, recreational aviation and training flights. Due to this, concepts like Flexible Use of Airspace (FUA) allowing a dynamic use of airspace between military and non-military airspace users have emerged to increase an efficient use of the airspace.

2.2.1.3 Business aviation

In business aviation flights are operated for a business purpose (e.g. charter flights) and are typically non-scheduled flights as opposed to commercial aviation. These flights can be frequently seen in the densest airspaces, although they are much rarer than commercial airlines flights. Business aviation aircraft are typically small jets, with cruising altitudes and speeds similar to commercial flights.

2.2.1.4 General aviation

The rest of aviation not included in the other groups, including rotorcraft, aerial work, recreational aviation and training flights amongst others. These users are out of the scope of the thesis since they typically operate in other airspaces (lower altitudes) than the ones which are the focus of the PhD thesis.

2.2.1.5 Unmanned Aerial vehicles (UAVs)

UAVs are expected to become an important airspace user in the future, replacing some of the traditional manned aircraft. At present, UAVs are not permitted to fly in non-segregated airspace, although the development of new regulations (e.g. (EASA, 2009)) plans to introduce these as normal airspace users, as long as they comply with existing safety standards. The research in this thesis does not aim to model the long-term operations of future air transport scenarios including the navigation of UAVs, fundamentally because this long-term concept of operations is still immature and not well defined.
2.2.2 Airport system

The airport is formed of landside and airside areas. Landside areas comprise access roads, parking lots and other facilities that enable the access of passengers and payload to the airport. Airside areas comprise taxiways, runways, apron and terminal buildings. Operations in the airside area of the aerodromes include arrivals, departures, taxiing and turn-around. This involves a significant number of stakeholders, including pilots, ground handling, tower controllers and emergency forces.

Airport operations are managed at two levels: strategic and tactical. The former accounts for planning activities in advance of the day of operation, mainly through slot scheduling, at the semi-annual IATA Slot Conference. Tactical activities on the day of operation may belong to one of the following groups: surface management, arrivals and departures management, turn-around and handling management and stand allocation.

Airports have traditionally been the main capacity limitation in the air transport system (Gilbo, 1993). This is due to the scarce availability of the airport resources (especially the runway) during high demand periods. Nevertheless, the focus of this research will not be on the landside but on the airspace, although it has to be noted that airport capacity constraints are an important area to be investigated within ATM modernisation programs. The justification for this is that it is reasonable to expect that if the airport limitation is gradually reduced (e.g. through higher use of secondary airports or reduced wake vortex operations among others) the airspace will increasingly become a larger bottleneck, hence it is necessary to start understanding already its nature.

2.2.3 Air Navigation Service Providers (ANSPs)

The ANSP is the stakeholder responsible for the safe management of air traffic within its volume of responsibility (EUROCONTROL, 2004b). In order to do this, ANSPs provide the traffic with services (fundamentally Air Traffic Control – ATC) in an airspace that has been organised to optimise flows respecting military, noise abatement and state boundaries constraints. These requirements aim to provide the airspace user with the necessary means to support their operation and at the same time maximise the delivered capacity.
In the case of military users, the military Air Traffic Service Units (ATSUs) operate as an equivalent military-ANSP. The ATC centres of the ATSUs can be located in the same facilities as the ATC centres of the ANSPs facilitating civil-military coordination. Although military operations and procedures differ significantly from civil ones, the organisation and sectorisation presented below apply to both.

2.2.3.1 Airspace organisation and phases of flight

In terms of the services provided, airspace can be fundamentally divided into controlled and uncontrolled airspace (Nolan, 1990). Controlled airspace is the focus of this thesis as it is the airspace in which capacity shortages typically arise. According to the portion of airspace where services are provided, the Air Traffic Services (ATSs) in controlled airspace are divided into three groups (ICAO, 2001b) (see Figure 2-1): airport control service, approach control service and area control service. These three groups are further associated with the typical phases of flight for airspace users (Figure 2-2).

Airport control service

ATSs are provided to aircraft on the airport surface or in the vicinity of the airport up to the boundary to approach control service or area control service i.e. the ConTRol zone (CTR). Airport control service is responsible for the taxi and take-off phases of flight.

The airport control service is typically located in the airport towers. Airport control in busy airports is usually divided into start-up control, taxi control and departure and arrival control in relation to the different phases of the aircraft activity on the airport ground and its vicinity.

Approach control service

The flights controlled within the approach control are in the arrival/departure phase. When many airports converge in the same area, the approach controls for the different airports are merged into a single TMA. Approach control is typically located in towers whilst TMA controls are located in separate control centres.

Approach control service is responsible for the early stages of climb, late stages of descent
and approach phases of flight. Approach control is usually divided into smaller airspace partitions in such a way that different units control the departure or the arrivals of air traffic from/to the airports.

**Area control service**

The area control service comprises all the controlled areas outside the two above (airport and approach control). Area control service is responsible for the cruise, late stages of climb and early stages of descent of flights.

The area control service is usually referred to as en-route control and is typically located in Area Control Centres (ACCs), which are in charge of a certain portion of airspace. When the control service is located over the seas and oceans where there is no radar coverage the centre is referred to as Oceanic Area Control Centre (OACC). The OACC controlling procedures differ significantly from the ones operating located over land. In fact, the control in the OACC is of a procedural type (see Table 2-1) not based on radar positioning but on estimated positioning made by pilot reports. The rules and separation distances differ from those used in ACCs. In areas of procedural control the separation standards are larger than in other areas due to the lack of positive positioning with radar systems (Nolan, 1990). This thesis will address the capacity assessment for en-route ACCs, where capacity shortages are typically found.
Figure 2-1 – Controlled airspace configuration

Figure 2-2 Phases of flight and control centres (Nolan, 1990)

60
En-route Area Control Centres (ACCs) sectorisation

The airspace under the control of ACCs is structured into a network of routes and smaller portions of airspace volume (Phillips and Marsh, 2000). These smaller portions have the main objective of easing the ATC function with a subsequent increase in safety and capacity (Welch et al., 2013). The specific manner in which the airspace is divided and configured is called airspace configuration or **sectorisation**.

Each of the indivisible airspace portions resulting from the airspace sectorisation is referred to as a *basic sector* in this thesis. Depending on operational conditions, such as weather or traffic flows, basic sectors can be combined differently resulting in different airspace volumes known as *operational sectors*, which are controlled by a team of ATCOs, each of the teams occupying an *operational position* inside the ACC operations room. An operational sector can therefore be either one basic sector or a combination of sectors. Each of the different combinations of basic sectors resulting in operational sectors corresponds to a unique *sector configuration*. An example of a set of airspace configurations is shown in Appendix 1 for the Delta-COastal sector group in MUAC.

In CHAPTER 3, the effect of airspace sectorisation on capacity will be discussed in detail and in CHAPTER 5 the staff requirements to use a certain airspace sectorisation and its effects on cost-efficiency will be investigated.

### 2.2.4 Regulators

The ATM regulators’ role is to ensure that all stakeholders comply with pre-defined rules. Regulatory bodies exist at national and international levels.

At a national level the body in charge of regulating is the so-called National Aviation Authority (NAA). At a European level, the regulator body is the European Aviation Safety Agency (EASA), which focuses on achieving a safe and environmentally friendly air transport system. EASA sets rules concerning airworthiness, air crew, air operations, Air Navigation Services (ANS) requirements, ATM safety, ATCO licensing, airspace usage
requirements and rules of the air (EASA, 2012).

Finally, due to the international nature of aviation, the International Civil Aviation Organisation (ICAO) focuses amongst others on standardising and harmonising the rules worldwide, to avoid fragmentation (see Section 2.4.4), promoting initiatives at an international level (Božičević, 2008). ICAO establishes the Standards And Recommended Practices (SARPs) covering all the regulatory areas and harmonisation between countries.

On the basis of the ATM system organisation and its primary objective, the following section details how the ATM system operates with the aim of understanding the complex relationships and internal processes developed by the different stakeholders during the execution of the ATM activities.

### 2.3 Current ATM System

Various models have been proposed in the literature to describe how the ATM system operates. In general, these models indicate the temporal horizon in which several identified functions are performed.

(Dehn et al., 2007) propose a barrier model in which the ATM system is seen as a chain of barriers, organised in three different groups named conflict prevention, conflict resolution and recovery, each aimed at avoiding aircraft collision with whatever information is available in that time-frame. (Hickson, 2004) takes a similar barrier approach, but focuses on the functions and tasks carried out by the ATCOs and their system. (Haraldsdottir et al., 2003) propose a time-functional model, establishing an ATM function for different time horizons from flight planning to execution. (Sipe and Moore, 2009) extend the previous model establishing a link between each function and the actor who is in charge of developing such function (in this case either the Airline Operations Centre (AOC), the airplane or ATC).

All these ATM models show the existence of functions performed by different actors in associated time horizons. The approach used in this section builds upon the findings of these models and is organised in the following dimensions, which are discussed below: functions, processes, roles and time-frames.
In the ATM system, actors develop specific tasks to accomplish certain ATM functions. In order to accomplish these functions, which are performed in different time-frames, the functions always follow the same structure, corresponding to invariant processes. Each of these processes is formed of several tasks that varies across the different actors or roles. The following subsections explain each of the dimensions.

The ATM system is currently defined as “the dynamic, integrated management of air traffic and airspace including air traffic services, airspace management and air traffic flow management — safely, economically and efficiently — through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions.” (ICAO, 2007). Given this definition, the ATM system is the result of the interaction of three main functions: Air Traffic Services (ATS), Air Traffic Flow Management (ATFM) and AirSpace Management (ASM) (Figure 2-3).

The ATM functions are formed of further sub-functions, which are defined in the sections below. The term ATM function is widely used in the literature often with different meanings (Aslaug Haraldsdottir, 1998, Dehn et al., 2007). In this thesis, an ATM function is defined as a service delivered by a stakeholder that is used by any other stakeholder involved in the development of the ATM activity.

Figure 2-3 – ATM services (ICAO, 2007)
In the ATM system flights progress from the airport of departure to the airport of destination across adjacent ACCs, which are further subdivided in operational sectors according to the instantaneous sector configuration. In the ACCs, tactical ground-based control of aircraft is performed locally (Section 2.2.3), along with global management of traffic flows (Section 2.3.2) and local optimisation of airspace (Section 2.3.3) to prevent operational sectors and airports from overloads.

2.3.1 Air Traffic Services (ATS)

The Air Traffic Services (ATS) function assists the flights during their execution. It is formed of the following sub-functions:

- Alerting service for emergency situations, (e.g. Search And Rescue operations)
- Flight Information Services (FIS) containing meteorological, aerodrome and possible flight hazards information
- Air traffic advisory providing more accurate services than FIS but not as Air Traffic Control (ATC)
- ATC services delivering clearances to prevent collisions and an expeditious and efficient flow of traffic (ICAO, 2005a). In the busiest areas of the European airspace, where capacity is a limiting factor, the service provided to the flights corresponds to ATC. This sub-function will be the focus of this thesis.

2.3.1.1 Air Traffic Control

ATC is the function of providing a safe, expeditious and orderly flow of traffic in the designated portion of airspace (ICAO, 2001b). The ATC function ensures no Loss Of Separation (LOS) occur while maintaining at the same time an efficient traffic flow. For this purpose, equipment, procedures and personnel interact in a complex manner to enable traffic separation and synchronisation and communication.

Aircraft are controlled according to their phase of flight by the relevant facility: aerodrome, approach and area centres (Section 2.2.3.1). Irrespective of the facility being considered, the process carried out by a control team can be generalised as follows:
1. Aircraft enter a sector;
2. ATC estimates future positions of the aircraft and detects conflicts between them;
3. ATC intervenes if necessary to separate the aircraft;
4. Aircraft exit the sector.

ATC provides the flights with clearances ensuring that separation minima requirements depending on factors such as meteorological conditions or navigation equipment are met. Separation minima standards are set and regulated by each country and are based on ICAO’s standards (ICAO, 2007). Typically in an European en-route ACC this separation standard is 5 Nautical miles (Nm) longitudinally and 1000 feet (ft) vertically.

The ATC function is implemented through support technologies, which are discussed in the following section.

### 2.3.1.2 Support technologies: CNS system

The ATC function is supported by Communication, Navigation and Surveillance (CNS) systems.

**Communication**

Information between functions is communicated through analogue and increasingly digital means. Traditionally the main ATC communication means has been the radio. Communication between ATC and aircraft is in the Very High Frequency (VHF) spectrum (108 to 137 MHz). In Europe, this band is divided in 8.33 KHz channel spacing allowing for 2280 different channels. When the number of required transmissions increases, these channels can become congested, leading to the need of additional communication links such as the Data-Link.

After information has been identified and communicated it is managed through processing systems. The large amount of data is managed by the Flight Data Processing System (FDPS), which gathers information from surveillance systems, processes it and transmits it to the ATC systems (e.g. air traffic display). The FDPS can additionally receive inputs from sources other than surveillance systems, for instance the ATCOs.
The FDPS updates the flight information when a clearance is given by an ATCO. Other information shared and circulating in the ATM system includes airport state (e.g. operating runway configuration) and weather. This information changes as it becomes available, ensuring a timely access, robustness and accuracy.

**Navigation**

The navigation systems provide information to the Flight Management System (FMS) in order to enable flights to travel from origin to destination as commanded by the ATC function. Several navigation systems have been implemented tailored to the different needs of air traffic for the different phases of flight.

During the approach and landing phases, the Instrument Landing System (ILS) provides the pilot with the lateral and vertical deviation of the flight descent path.

In the en-route phase of flight navigational aids such as the VOR, the Non-Directional Beacon (NDB) or the airborne Inertial Navigation System (INS) helps navigating the aircraft to the next point in the flight plan. Currently the implementation of the aRea NAVigation (RNAV) navigational method, which enables navigation through non-fixed ground-based navigational aids, such as the case of the VOR and NDB, enables a more flexible and optimised navigation performance.

**Surveillance**

The purpose of the ATM surveillance system is to determine aircraft position and state. In an ACC the traditional system has been the Primary Surveillance Radar (PSR). The PSR computes aircraft positions from the travel time of a pulsed beam of ultrahigh frequency radio waves reflected by the aircraft. PSR surveillance has been widely enhanced in Europe by Secondary Surveillance Radar (SSR). The SSR is an improvement over the PSR and interrogates dedicated airborne equipment about the position and other flight indicators (e.g. ground speed, selected altitude, climb rate and course amongst others) of the aircraft. This information is transmitted back to the radar through an airborne transponder. This surveillance mode is referred to as “Mode S” and is an active rather than a passive technology, as opposed to PSR.
In the event of failure of the ATC function, LOSs can potentially occur. To prevent air traffic collisions, a collision avoidance function is implemented in the current ATM system when the other functions (mainly ATC) have been unsuccessful in accomplishing this objective. The collision avoidance function is therefore a safety net.

The Traffic Collision Avoidance System (TCAS) is the standardised airborne safety net (ICAO, 2007). The TCAS operates based on SSR interrogations and provides different alerts and clearances to the pilot depending on the relative position and course of the conflicting flights (ICAO, 2010). A TCAS resolution clearance overrides any other instruction by the ATCO.

The ground-based Short Term Conflict Avoidance (STCA) provides the ATCO with warnings of LOS. Since, unlike the TCAS, the STCA is not a standardised system, its implementation may vary between centres.

Other safety nets include the ground-based Runway Incursion Monitoring and Collision Avoidance System (RIMCAS) to prevent aircraft runway incursions and the Minimum Safe Altitude Warning (MSAW) system to warn ATCOs when flights are flying towards obstacles on the terrain.

### 2.3.2 Air Traffic Flow & Capacity Management (ATFCM) function

The objective of the ATFCM function is "to provide sufficient capacity to accommodate the demand in typical busy hour periods without imposing significant operational, economic or environmental penalties under normal circumstances" (EUROCONTROL, 2005). In order to achieve this goal the ATFCM function pursues the following secondary objectives (Commission, 2010, ICAO, 2001b):

1. Prevent traffic over-deliveries. An over-delivery is defined as an excess of air traffic demand that can be subsequently be translated into an overload for the ATC function.
2. Optimise the network efficiency and minimise adverse effects by making optimal use of available capacity i.e. maximise the airspace utilization.
3. Enhance the maximum capacity through the development and application of specific measures.
4. Manage critical events (e.g. weather disturbances: volcanic ash) in order to make use of the available resources.

The ATFCM function has its origins in the ATFM function (Section 2.1). The difference is based on the greater stress of the ATFCM function on objectives 1 and 2 by means of balancing demand and capacity optimising available resources and implementing responses (EUROCONTROL, 2012a).

ATFCM is implemented as a time refinement process as more accurate information becomes progressively available. During the execution phase measures are implemented in order to fulfil the ATFCM mission goals. These measures are (EUROCONTROL, 2012a):

- **Regulation**: consists in the allocation of a departure slot. In Europe the regulation slot is calculated through the Computer Assisted Slot Allocation (CASA) process (Cook, 2007).
- **Re-routing**: change in the flight plan e.g. flying an alternative air route.
- **Level capping**: change in the flown flight levels e.g. restricting the highest flight level that an aircraft can take to avoid this flight entering a congested higher airspace.

The ATFCM function in Europe is implemented through the so-called Enhanced Tactical Flow Management System (ETFMS). The ETFMS receives information on flight plans from airspace users, environment data and flight data updates from ATC centres (e.g. ACCs) in order to provide two main services:

- **Traffic demand calculation**: this information is subsequently used by ATFCM users to appropriately implement measures that ensure a balance between traffic and demand
- **Computer Assisted Slot Allocation (CASA)**: this process assigns departure slots, cleared as a Calculated Take-Off Time (CTOT), to the regulated flights. The departure slot window has a -5 to +10 minutes tolerance relative to the cleared CTOT.

### 2.3.3 Airspace Management (ASM)

ASM measures are major contributors to the demand and capacity balancing task, applied through the ATFCM measures (EUROCONTROL, 2004a): the ASM function designs
optimum airspace configurations, in terms of routes and sectorisations aiming to satisfy airspace users requirements (fundamentally route flexibility) at the same time as ATC centres requirements (ease of controllability) (ICAO, 2001b).

During the execution phase, the ASM management function directly assists the ATFCM function optimising capacity resources and avoiding over-deliveries by means of providing the optimum sector configuration i.e. configuration management. Configuration management selects the optimum sector configuration based on (EUROCONTROL, 2005):

- Traffic pattern predictions
- Weather predictions
- Available sector configurations
- Staff availability
- Event predictions
- Military activity

“Splitting” operational sectors is a measure that increases capacity, whereas “collapsing” or “combining” operational sectors reduces the capacity. This procedure is typically used to ensure an airspace configuration is tailored to the traffic demand and operational needs (see CHAPTER 3 for further details).

Splitting airspace volumes into smaller operational sectors has been the main enabler for increasing airspace capacity, which does not involve any substantial technological change. Even though the absolute traffic levels for smaller airspace sectors are reduced compared to larger sectors, the former can handle more traffic density, hence releasing capacity enhancements (Welch et al., 2007).

Since the ATCO has been the main airspace capacity bottleneck (CHAPTER 3), the division of the airspace into more operational sectors operated by additional ATCO pairs, enables the spread and re-distribution of the workload (Section 3.4) across the different operational sectors, thus increasing capacity. However, the increases in airspace capacity due to re-sectorisation are not unlimited.

Figure 2-4 shows the effect of opening additional operational sectors (x-axis) on the
maximum capacity for the airspace configuration (measured in maximum instantaneous aircraft i.e. maximum occupancy). This trend is calculated for the three sector groups in MUAC: Brussels (blue), DElta-COastal (green) and Hannover. Each sector group is formed of several basic sectors, which are listed in Appendix 4.

For each of the three sectors, it is observed that the maximum occupancy increases as the number of open operational sectors increases. However, the increases become smaller the larger the number of open operational sectors.

![Graph showing maximum occupancy as a function of open operational sectors for MUAC sector groups](image)

Figure 2-4 Maximum occupancy as a function of open operational sectors for MUAC sectors groups

When the configuration cannot be further split or when no additional staff is available to open additional operational sectors, demand may overshoot capacity, resulting in ATFCM measures being required to prevent traffic over-deliveries. This explains how closely ASM and ATFCM operate and suggests a need to analyse both together to understand their combined impacts on airspace capacity.

In addition, the ASM function also coordinates the ACC/military ATSUs airspace needs, by means of route provisions, such as ConDitional Routes (CDRs) and volumes to be used for different airspace users. This is the so-called FUA.
2.3.4 Long-term planning

The long-term planning function, which is not included in (ICAO, 2007) encompasses all the strategic planning processes of the ATM system. This fundamentally includes planning activities at network and local (ATC centre and airport) levels.

The ATM system makes use of expensive resources such as the ATCOs. ATCOs control ATC operational sectors and airports that are constrained in capacity. As introduced in Section 2.3.3 splitting operational sectors results in increased airspace capacity. This can be achieved only at the expense of a more intensive use of ATCOs resources. Therefore to enable an optimum performance of the ASM function, it is necessary to plan the workforce necessary for any given day ahead of the actual day of operation.

In addition, ATC centres need to estimate and develop the long-term operational requirements in terms of future technologies, procedures and operations. The network planning process gathers the plans and predictions from ATC centres and airlines in order to build a holistic prediction of the network, aiming to detect possible imbalances and support as well the local planning processes. In Europe this function is carried out annually by EUROCONTROL through the process shown in Figure 2-5 (EUROCONTROL, 2007).
This process involves assessing past performance in capacity terms (fundamentally delays), and making an extrapolation of future performance based on traffic forecasts and local capacity increases. These local capacity increases are calculated by each ACC or airport, based on their modernisation and implementation plans. This process is carried out through techniques supported fundamentally by Fast Time Simulations (FTS) (see more in CHAPTER 4).

This section has introduced the ATM functions (collision avoidance, ATC, ATFCM, ASM and long-term planning functions). These functions are developed in a uniquely structured manner based on invariant processes, which are outlined in the next section.

2.3.5 The ATM invariant processes

The ATM system is formed of different actors that accomplish functions based on the nature of their own roles and the needs of the system. Although the actions and responsibilities vary
across the actors (see Section 2.3.6), the processes accomplished to achieve their objectives remain invariant. These invariant processes are the following: predict, detect and resolve (Figure 2-6). The first three processes are applied in a sequential manner and they are continuously supported by the communication & information management process.

![Diagram showing the processes of predict, detect, resolve, and communication & information management.]

Figure 2-6 ATM invariant processes

The flow of processes is applied to each of the functions identified. Nevertheless, what it is actually being predicted, detected, resolved and communicated differs (Table 2-2).

Table 2-2 – Processes and roles mapping

<table>
<thead>
<tr>
<th></th>
<th>Predict</th>
<th>Detect</th>
<th>Resolve</th>
<th>Communicate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Collision Avoidance</strong></td>
<td>Positions</td>
<td>Collision</td>
<td>Climb/descend resolutions</td>
<td>Involved pilots</td>
</tr>
<tr>
<td><strong>ATC</strong></td>
<td>Positions</td>
<td>Conflicts</td>
<td>Vector, speed, climb/descent…</td>
<td>Pilot, other ATCOs</td>
</tr>
<tr>
<td><strong>ASM</strong></td>
<td>Traffic demand</td>
<td>Sectorisation imbalance</td>
<td>Airspace configuration</td>
<td>Other ATC centres</td>
</tr>
<tr>
<td><strong>ATFCM</strong></td>
<td>Traffic demand</td>
<td>Demand/capacity imbalances</td>
<td>Delay, re-routing or level capping</td>
<td>To airspace users, airports and ATC centres</td>
</tr>
<tr>
<td><strong>Long-term Planning</strong></td>
<td>Traffic Demand</td>
<td>Demand/capacity imbalances</td>
<td>Capacity enhancements</td>
<td>Network stakeholders</td>
</tr>
</tbody>
</table>
The sections below describe each of the processes in detail.

2.3.5.1 Prediction

Accurate predictions are crucial for an optimum performance of the ATM system, since they enable advance optimisation and make the system less reactive (Ruigrok et al., 2002). However, this is a complex task due to the intrinsic uncertainty of the system (Ehrmanntraut, 2010). These predictions can be of different natures: trajectory predictions, weather predictions, traffic demand predictions or workload/complexity predictions amongst others. System predictability depends on the phase of flight, operational conditions (e.g. weather) and equipment both airborne and ground-based (Section 6.1).

2.3.5.2 Detection

Based on the predictions made by the different functions, a detection of system imbalances and inefficiencies is accomplished. The detection process can lead to triggering resolution actions if imbalances or inefficiencies have been detected. Demand/capacity imbalances, conflicts, losses of separations are examples of the circumstances being searched for detection.

2.3.5.3 Resolution

When an imbalance or inefficiency is detected based on a prediction, it needs to be resolved to ensure meeting the ATM objectives. Resolution strategies differ depending on the nature of the detected imbalance or inefficiency. The resolution process makes the ATM system a controlled system, in which actions are performed to maintain the system performance within acceptable performance boundaries.

2.3.5.4 Communication & information management

The three processes above are supported by communication and information management, to ensure that all relevant stakeholders in the ATM system have access to timely and accurate data. Communication is in charge of providing the means to allow a point-to-point transfer of information whilst information management carries out data aggregation to ensure that
information is accessible to stakeholders under request.

The section below outlines the principal roles in each of the functions.

2.3.6 The ATM roles

In this thesis, the ATM roles are not necessarily physically existing actors, but functional roles that participate in the development of certain ATM functions e.g. one physically existing actor could embed to functional roles. These functional roles are described in the sections below.

2.3.6.1 The Air Traffic Controller

The traffic on the airport surface, in its surrounding airspace and in the higher airspace levels is controlled by ATCOs. The ATCO mission is to ensure the ATC main objectives i.e. accomplish a safe, ordered and expeditious traffic flow (Seamster et al., 1993). In general, in en-route ACCs, the ATC is managed by a team of two ATCOs (Board, 2010):

- The radar, tactical or Executive Controller (EC)
- The Planning or Coordinator Controller (PC)

The EC is responsible for the separation of traffic within their operational sector boundaries, while the PC assists the radar ATCO in their tasks and ensures coordination between adjacent operational sectors.

Nevertheless, the double-ATCO configuration is not ubiquitous across ATC centres. In ATC centres such as approach control and airport towers, configurations are variable according to operational requirements, and tending to single-ATCO operations (Tien and Hoffman, 2009). Even at en-route ACCs the two-manned configuration for en-route ACC may be adapted for special situations such as the ones following:

- Training: where one ATCO is the trainee (training either as an EC or as a PC), another ATCO is the coach and the last one is the EC or the PC depending on the trainee role.
- Very busy scenarios: where one ATCO, the assistant, is introduced acting as support
ATCO.

In en-route ACCs ATCO workload is the main capacity bottleneck (Majumdar, 2003) (Section 3.4). Therefore, the understanding of this role is of paramount importance to address the airspace capacity problem. This section highlights the main characteristics of the ATCO role in the ATM system. A more detailed discussion on the effects of ATCO job in airspace capacity, fundamentally through ATCO workload can be found in CHAPTER 3.

The ATCOs team job can be broken down in terms of goals, tasks and external resources. In order to accomplish their goals, ATCOs carry out tasks, both physical and cognitive with the help of external resources.

The ATCOs team goals are objectives pursued in order to provide traffic separation and synchronisation i.e. ATC service-oriented goals. However, other goals that are not oriented to the airspace user can be found as well. These are the cognitive-oriented goals, or objectives accomplished to support the own ATCO activities. (Dehn et al., 2007) identify the following ATCO goals:

<table>
<thead>
<tr>
<th>ATC service goals</th>
<th>Support goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conflict avoidance</td>
<td>Confirm &amp; update mental picture</td>
</tr>
<tr>
<td>Tactical de-confliction</td>
<td>Workload monitoring</td>
</tr>
<tr>
<td>Coordination &amp; transfer</td>
<td>Flight progress monitoring</td>
</tr>
</tbody>
</table>

In accomplishing these objectives, ATCOs develop different tasks. The ATCOs’ tasks are identified in the task analyses, which can be divided in different types according to the characteristics specified in (FAA, 2010, RHEA, 1997):

- The level of granularity of the study.
- The specific ATCO working procedures i.e. differences between trainings.
- The specific airspace procedures e.g. lower vs. upper airspace or small vs. large operational sectors.
- Task identification method used.
(Rodgers and Dreschsler, 1993) group ATCO tasks into one of five categories: monitoring, conflict detection, conflict resolution, communications and data entry. A similar task taxonomy is used in (Pawlak et al., 1996) with a further distinction between physical and cognitive tasks. Physical tasks include an observable action made by the ATCO (e.g. making an input to the system), whilst cognitive tasks cannot be observed and belong to the ATCO cognition (e.g. predicting the future position of a flight).

Whilst in the past, task analysis and modelling of the ATCO job have been fundamentally based on the directly-observable physical tasks identification, recent research e.g. (Loft et al., 2007) has shown that fundamental human performance indicators such as ATCO workload cannot be accurately estimated based on physical tasks alone. In practice, the ATCO cognitive tasks are a much more precise indicator of human performance, as they govern the ATCO core activities (Sperandio, 1978), and should therefore be the aim of the task analyses (Section 4.2.1.2).

Depending on the focus of the task analysis, these can be cognitive-oriented or action-oriented. The action-oriented task analysis is focused on the physical actions carried out by the ATCO. A hierarchical structure between the action-oriented ATCO tasks has been the classic way of characterising the ATCO job (Cox et al., 2007, Endsley and Rodgers, 1994, Mills et al., 2002, Phillips and Melville, 1988, Vortac et al., 1994). Controller command, controller query, pilot request, sector transitions, team communication, look, write, manipulate, update computer, obtain computer information, conflict detection, computer handoff are examples of the tasks identified in (Vortac et al., 1994).

Cognitive-oriented task analysis is focused on the mental processes carried out by the ATCO (Sperandio, 1978, Signal, 1997, Seamster et al., 1993, Eyferth et al., 2003) and eventually in the relationship of these cognitive tasks with the physical actions (Kallus et al., 1998). Multitasking, direct attention to information sources, process of external information, memory management, planning, decision-making, diagnosis and problem solving, team awareness are examples of tasks identified in (Low, 2004).

In CHAPTER 8, a task analysis of MUAC ATCOs will be carried out in order to develop a workload estimation methodology. This task analysis will be an action-oriented task analysis,
although these physical tasks will reflect the cognitive actions associated with them.

Finally, the ATCO makes use of external resources to gather information and subsequently trigger tasks to achieve the goals. Resources, such as other ATCOs, automation or pilots, are used as support.

ATCOs in ACCs work in pairs surrounded by other ATCOs in other operational positions in the ACC, working closely with other ATCOs from adjacent operational sectors in other ACCs. Teamwork is therefore a key element of the ATCO job and has recently raised interest of ergonomic researchers in ATC e.g. (Nonose et al., 2010).

Other sources of information are the pilots, who inform ATCOs on the current and projected state of the flight, supplementing the information gathered by the surveillance systems. Some of this information is currently being replaced through automated surveillance functions (e.g. SSR), which either automatically, or following request, provide various flight indicators (e.g. ground speed). This method alleviates the radio-frequency ATCO-pilot congestion, avoids communication misunderstandings and accelerates the communication process.

The final source of information comes from automated systems, fundamentally the FDPS. In order to cope with today’s air traffic complexity in the busiest of European airspace, enhanced support from automated systems is necessary. The ATCO support systems include a variety of tools that differ across ACCs depending on the specific needs of each centre (Voller and Low, 2004).

2.3.6.2 The Pilot

The pilot is responsible for the safety and control of the aircraft during the flight (ICAO, 2005a). Pilots aviate (control the aircraft), navigate (find the aircraft position and fly to destination), communicate (to/from ATC mainly) and act as an aircraft systems administrator (Jonsson and Ricks, August 1995).

Traditionally the interaction between the pilot and the ATCO has been via radio communication: two-way channel communication. This has led to the congestion of the radio frequency, with associated capacity constraints (Corker et al., 2004, Manning and Pfleiderer,
2006, Manning et al., 2001). Currently, the introduction of the Controller-Pilot Data Link Communication (CPDLC) channel is overcoming some of these problems.

2.3.6.3 Executive Operations Support

Executive Operations Support (EOS) is comprised of operation room supervisors, Flow Management Position operators (FMPs) and flight data operators. Their mission is to support the ATC operation execution and ATCOs. In small ACCs or during night-times the above three roles can be assumed by a single operations room supervisor.

The operations executive supervisor is an executive role in charge of the overall operations at the ATC operations room. This role has an integrated view of the situation within the airspace of responsibility, able to optimise operations inside that airspace. The executive supervisor objectives are as follows (EUROCONTROL, 2005):

- Supervise the operations room.
- Manage critical events.
- Supervise the development of the ASM and ATFCM functions.
- Manage available ATCO staff.

The executive supervisor is supported fundamentally by the FMP, whose missions comprise the following (CFMU, 2012):

- Demand supervision – traffic over-delivery avoidance.
- ATFCM and ASM functions development.
- Traffic Load Monitoring.
- Support to the executive supervisor.

Finally, flight data operators ensure that all the flights entering the airspace have filed a flight plan, generating one when it is missing. With the introduction of new flight data processing systems and increased collaboration between centres this role is today being progressively relegated.
2.3.6.4 Network Manager

The Network Manager (NM) is responsible for the European network as a whole. The NM supervises the network and acts as a node for information sharing in Europe. The origins of the NM go back to the Central Flow Management Unit (CFMU), which became fully operational in 1996. Initially the CFMU provided capacity management through the slot allocation process provided by the CASA method. Later on, it introduced other capacity management measures such as re-routings and level cappings. The CFMU today, still performs the ATFCM function locally for those centres not having these capabilities. It coordinates ATFCM measures involving different centres, implements ground delays through the CASA method and processes the flight plans for all the flights crossing European airspace, sharing this amongst the relevant stakeholders.

Additionally the NM is in charge of activities such as crisis management (e.g. volcanic ash) and post-operation analysis and reporting.

2.3.6.5 Automated systems

Various authors define automation as the introduction of autonomous systems (Billings, 1996, Wickens et al., 1998) which replace former human tasks (Parasuraman et al., 2000) (Funk et al., 1999) or aid the human decision making process (Villiers, 1975). In the air transport system, automation can be found in the aircraft and on the ground. Airborne automation fundamentally supports the control and navigation of the aircraft through its main computer, the FMS.

Whilst enhancing safety, e.g. through the introduction of TCAS, the airborne automation systems have hardly impacted airspace capacity. Ground automation equipment though has made a direct contribution to ATC execution performance and hence capacity. Due to the increasing relevance of ground-automation on airspace capacity, this will be the focus of the thesis.

Ground automation, or just automation as it is referred to in this thesis, can be deployed in different areas as shown in (Voller and Low, 2004, Hopkin, 1995, Wickens et al., 1998). (Parasuraman et al., 2000) associate these deployment areas with one of the following ATCO
cognitive processes:

- Information acquisition.
- Information analysis.
- Decision and action selection.
- Action implementation.

(Hopkin, 1995) distinguishes between automation where the machine fulfils a function and computer assistance where the machine helps the human carrying out the function. The more an automated system contributes towards fulfilling a given task, the more automated the function is. This has been addressed traditionally from the perspective of the levels of automation (Wickens et al., 1998, Billings, 1996, Maxwell, 1975, Hopkin, 1995, Parasuraman et al., 2000, Endsley, 1996, Voller and Low, 2004, Hollnagel and Woods, 2005).

The levels of automation define, for the different automation deployment areas, the degree of assistance of the machine, from unassisted to autonomous operations (Table 2-4).

Table 2-4 Levels of automation of decision and action selection (Parasuraman et al., 2000)

<table>
<thead>
<tr>
<th>Level of automation</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (High)</td>
<td>The computer decides everything, ignoring the human</td>
</tr>
<tr>
<td>9</td>
<td>Informs the human only if the computers decides to</td>
</tr>
<tr>
<td>8</td>
<td>Informs the human only if asked</td>
</tr>
<tr>
<td>7</td>
<td>Executes automatically and informs the human</td>
</tr>
<tr>
<td>6</td>
<td>Allows the human a restricted time to veto before automated execution</td>
</tr>
<tr>
<td>5</td>
<td>Executes that suggestion if the human approves</td>
</tr>
<tr>
<td>4</td>
<td>Suggests one alternative option</td>
</tr>
<tr>
<td>3</td>
<td>Narrows the selection down to a few</td>
</tr>
<tr>
<td>2</td>
<td>The computer offers a complete set of decision/action alternatives</td>
</tr>
<tr>
<td>1 (Low)</td>
<td>The computer offers no assistance</td>
</tr>
</tbody>
</table>

The quantification of the impact that the introduction of automation has had on ATCO
performance is of key importance. (Goodwin, 1980) argues that full automation in ATM is not a feasible option due to the safety implications of this configuration. This approach is supported by the findings of (Lisanne, 1983) on degraded performance of human-automation systems due to increased responsibilities attributed to automated systems. (Prevot et al., 2012) suggests that medium automation levels where a collaborative interaction between the human and the system occurs is more likely to succeed than a configuration with the two roles working in isolation.

From a human factors point of view, several studies have been carried out to assess the impact of automation, looking at the following performance areas:

- Workload (Low, 2004, Kaber et al., 2007)
- Situational awareness (Endsley, 1996)
- Cognition (Kirwan, 2001, Bisseret, 1971)
- Human error (Kirwan, 2001)
- Team performance (Leroux, 1998, Langan-Fox et al., 2009)
- Skill requirements (Voller and Low, 2004)
- Controller behaviour (Vortac et al., 1994)

Therefore, the effects of automation on human performance are of paramount importance in developing new systems and procedures for ATC as they indicate the suitability of the new enhancements on ensuring more efficient ATC operations (Kirwan, 2001).

Automation can also be deployed to support other roles and functions other than the ATCO during the ATC function execution. In fact, as discussed in the following chapters, automation can have a direct effect on airspace capacity.

Examples of automation in other ATM functions include workforce management tools (CHAPTER 5) and air traffic prediction tools (CHAPTER 6). These two types of automation support the long-term planning and ASM/ATFCM functions respectively.

Figure 2-7 outlines the relationships between the already introduced ATM roles: pilot, ATCOs (both EC and PC), EOS and the system or automation (S). This diagram is derived from the observations made in the MUAC centre (CHAPTER 8) and has been validated by
SMEs (ATCOs and FMPs) of this ATC centre. The figure shows the relationships between the different actors within the same operational sector, across different operation sectors and across different ACCs.

![Diagram showing relationships between different ATM roles](image)

Figure 2-7 Relationships between the different ATM roles (based on MUAC operations)

This figure further shows the close relationships between the actors in charge of developing the ATC function (ATCOs) and the actors in charge of developing the ASM/ATFCM functions (FMPs and NM). With the introduction of modernisation initiatives these relationships are envisaged to become even stronger with more crucial roles to the ASM and ATFCM functions (Section 2.5).

### 2.3.6.6 Airline dispatcher

The airline or flight dispatcher is the operational actor connecting the pilot and the Airline Operations Centre (AOC). The flight dispatcher is partly-responsible for the safety of the
operation, although his/her main responsibilities include as well the efficiency of the airline operation from an integrated fleet perspective. In order to do this, they monitor flights and make changes to flight plans including take-off times in order to meet the airline objectives.

2.3.7 The time-frames

ATM operational planning goes through an iterative refinement process, in which different layered measures are applied to optimise the operations as more accurate information becomes progressively available. Therefore, the different roles, tasks and functions are individually associated with a certain temporal layer or time-frame.

The time-frames are defined as periods of time relative to the absolute execution time of the flight. No agreement is found in the literature on how to name or to define the different time-frames of the ATM system (Haraldsdottir et al., 1997). In this thesis the following will be used:

- Long-term: More than 6 months before flight execution day.
- Strategic: 6 months to one day before the flight execution day.
- Pre-Tactical: one day before to approximately 20 minutes before a given instant in the flight trajectory (e.g. enter to a certain airspace).
- Tactical: from approximately 20 minutes before to the actual flight trajectory instant.
- Execution: relative zero time.
- Post-execution: after flight execution.

The previous sections have introduced the ATM functions, invariant processes, roles and time-frames. The next section maps time-frames, roles and functions between them (processes remain invariant and ubiquitous to every ATM function).

2.3.8 Mapping of roles, time-frames, processes and functions

Figure 2-8 maps the ATM roles, their associated functions and the time-frame between them.
As observed in Figure 2-8, the ATM roles are uniquely associated with an ATM function and in turn with a given time-frame. The only exception is the EOS, who develops both the ASM and ATFCM functions, even though it was previously seen (Section 2.3.3) that both functions have a great degree of overlap and cooperation.

This section has shown the architecture of the current ATM system. This system has a number of inefficiencies that have motivated the creation of modernisation initiatives. These inefficiencies are detailed in the next section.

2.4 Current System Limitations

Eurocontrol characterises the performance of the air transport network in terms of Key Performance Indicators (KPIs). The following KPIs analysed in (PRC, 2011), capture the state of the ATM system:
- Punctuality: more than 20% of fights are delayed by more than 15 minutes.
- Increase of actual distances flown: mean increases of 49.1 kilometres per flight.
- Cost-effectiveness: 0.8€ of en/route air navigation services costs per kilometre flown.
- Safety: the often weak reporting methods for safety incidents in many countries make the analysis of true safety levels very difficult. In spite of this, in 2010 there were a total of 273 separation infringements, runway incursions and unauthorised penetrations in controlled airspace.

A key number of weaknesses have been identified. (Ratcliffe, 1985) identifies coordination between centres, rigid airspace structure and local, as opposed to global optimisation, as the fundamental ATM system limitations. (ICAO, 2005b, SESAR, 2008c) identify current system limitations which are discussed below in higher depth.

2.4.1 Radio communication congestion

Communications between the EC and pilots within the operational sector are achieved through radio communication messages (apart from CPDLC messages). These communications follow a set of techniques (ICAO, 2001a) including specific phraseology and flow (Figure 2-9).

![Figure 2-9 ATCO-pilot communications flow](image)

Flights in an operational sector make use of the same radio frequency to communicate with the ATCO. When the number of aircraft rises, communication channels become increasingly saturated and the following events can occur (Skybrary, 2013):
• The ATCO and/or pilot are unable to communicate timely important information e.g. request confirmation or clarification.
• **Blocked communications** occur when a pilot communication is not heard due to another pilot using the radio-frequency channel. This happens when two or more pilots try to use the radio-frequency at the same time.
• Call-sign confusion: ATCOs refer to the flights using its name or call sign. Pilots can take incorrect actions if they incorrectly interpret the call sign.

These communication inefficiencies can increase pilot and ATCO workload to resolve confusions and clarify instructions (Section 3.4). These issues are expected to be addressed through the progressive introduction of CPDLC in the most congested airspaces.

### 2.4.2 Poor predictability

Prior to the actual execution of an operation, potential changes in constraints may occur. As a result, the system becomes reactive and non-optimal decisions and solutions are applied. Predictability is a metric of the variability of the ATM system due to its inherent uncertainty (Bolczak et al., 1997). Predictability has two dimensions: the Look-Ahead Time (LAT) and the accuracy of the prediction.

Depending on the purpose of the prediction, the predictability requirements differ. For instance, for the network planning function (large LAT) the total number of flights in a day may be sufficient to accomplish the function objective (predicting the daily traffic demand), whilst for the ATC function (short LAT), accuracies of the sector entry time better than one minute may be necessary for LATs of 1 hour. The current predictability of the ATM system is further discussed in CHAPTER 6.

For ATC, predictability is needed to estimate the future position of the aircraft. This is necessary to predict, detect and resolve air traffic conflicts. In the current ATM system, ATCOs predict the future position of the aircraft mentally. When the position predictions do not accurately reflect the actual flight performance, situational awareness can decrease (Section 2.3.6.1), leading to the ATCO performance becoming more reactive. In order to avoid reactive working procedures, which can compromise safety, some ACCs have
implemented DSTs to support the ATCO prediction process.

The most popular DST that increases the system predictability is the Medium Term Conflict Detection (MTCD) tool (Kauppinen et al., 2002). However, experience shows that accurate predictions are needed in order to avoid increasing workload (rather than reducing it) of ATCOs through false alerts (Tamvclis et al., 2004). Today’s ATM system still lacks an appropriate level of ATC predictability and relies fundamentally on ATCO cognitive processes.

In the ASM and ATFCM functions, low predictabilities can lead to non-optimal operations, linked to under-utilisation of resources, e.g. open operational sectors, or penalties such as delays. In addition an incorrect prediction can have a safety impact if, for instance, over-deliveries are not predicted. The negative effects of the lack of predictability for the ASM and ATFCM functions are discussed in CHAPTER 5 and CHAPTER 7 respectively.

In the network planning function, a poor prediction usually leads to network cost-inefficient operations. In these cases, some resources (ACCs) may be used to their full capacity while other more developed ACCs are not making use of their full potential due to the network bottleneck imposed by under-developed ACCs.

2.4.3 Airports performance

According to (PRC, 2011), ten major European airports are currently congested several hours each day, and are the main capacity bottleneck of the ATM system at a network level (SESAR, 2006). Delays produced on the airport surface or in the Terminal Manoeuvring Area (TMA) have a network level impact in terms of reactionary delays affecting the overall network.

The high sensitivity of airport and TMA operations to weather conditions represents a fundamental limitation of the ATM system (Klein et al., 2009). Current surveillance and guidance techniques, as well as inefficient procedures, cannot accommodate the expected throughput when weather conditions deteriorate.
2.4.4 Fragmentation

Under the 1944 Chicago Convention, states have sovereignty over their national airspace, leading to fragmentation at an operational level. In Europe, today, there are 40 ANSPs and 64 ACCs. These ANSPs have sovereignty over their airspace and are in charge of ensuring the safe flow of aircraft across it. The boundaries of the airspace usually correspond to the landside limits of the country. This kind of airspace partition, which has not been designed taking into account the requirements of the air traffic, leads to significant inefficiencies in the ATC function.

At a system level, fragmentation can be found in the following (Helios, 2006):

- ATC systems: each of the ANSPs use their own ATC system which are not interoperable with neighbouring ones. As a result, information is not appropriately used and shared. In addition, developments for an enhanced system are usually slowed down due to system incompatibilities. Costs from this fragmentation include duplicate maintenance.
- Communications, navigation and surveillance infrastructure: this fragmentation leads to sub-optimal location of navigation aids and duplicate maintenance costs.

Finally the economies of scale of the different ACCs and ANSPs include fragmentation in domains such as training, inconsistent system developments and in general sub-optimal implementations.

2.4.5 Low information sharing

The lack of information sharing is a key contributing factor in the reactive nature of the ATM system. The fragmentation introduced above, in addition to inefficient information sharing procedures, limits the ability of the system to predict and optimise future scenarios, i.e. the system becomes tactical.

The ATM functions cannot optimise their performance if they are lacking the necessary information to carry out their internal processes. Therefore, information integration and sharing is needed. Apart from the technological factors that prevent information sharing, the
business value of the information is another factor: airspace users are reluctant to share information that may reveal business models and strategies, which can decrease their competitive advantage (airlines) or reveal highly sensitive information (military users).

2.5 ATM Modernisation Initiatives

The current modernisation initiatives in the ATM system have their origins in the 1980’s decade. During that time it was already realised that with the existing procedures and technologies, the ATM system would soon become limited in terms of safety, efficiency, capacity and with significant environmental footprints. Therefore, in 1983 the Future Air Navigation Systems (FANS) program was established by the ICAO to develop the future air navigation system. This future concept became called as the “CNS/ATM system”.

The technologies and procedures envisioned in the CNS/ATM system were in need of an implementation plan able to harmonise the various technical developments, resulting in a global and integrated ATM system. To this aim, the ICAO developed the Global ATM Operational Concept (ICAO, 2005b), which is the current guide for worldwide ATM modernisation initiatives.

In Europe, in order to resolve the current ATM system inefficiencies and to achieve higher environmental, safety and cost-effectiveness performance, the European Commission launched the Single European Sky (SES) ATM modernisation programme in 1999. This European programme is developed in reference to the ICAO Global ATM operational Concept, even though the concept is tailored to the inherent characteristics of the European Air Traffic Management system.

The SESAR programme has developed a target operational concept, which is foreseen to be implemented in three successive steps. In each of those steps deployment packages will be implemented through a set of Operational Improvement Steps (OISs). As this information is currently frequently updated, the website https://www.atmmasterplan.eu/home provides the latest version of the all the implementation plans. Appendix 2 shows the SESAR Master Plan OISs for the April 2014 version. Throughout the thesis, the OISs will be referred to in cursive font with the OIS abbreviation followed by its title e.g. CM-0801 - Ground Based Safety
2.5.1 The ATM target concept

The ATM target concept in Europe is performance-based, centred around Trajectory-Based Operations (TBOs) (SESAR, 2007b). TBOs will not be implemented in isolation. They will require the introduction of other technologies (e.g. satellite navigation) and procedures (e.g. air-to-air data exchange) and will enable the deployment of new operations thanks to its new features (e.g. airborne separation).

Figure 2-10 depicts the key changes and their essential elements in the evolution from the pre-SESAR (i.e. prior to the start of SESAR deployment) to the SESAR ATM systems.

![Figure 2-10: From the current ATM system to the ATM target concept (SESAR) (adapted from (Schuster and Ochieng, 2010))](image-url)
Figure 2-10 captures the paradigm shift in seven features. The fundamental shift is the change from current airspace-based operations to TBOs. This change consists in the flight of aircraft using non-airspace bounded instructions, bounded only by trajectory capabilities. For instance, in today’s system, flights generally progress through the airspace through pre-defined airspace structures or airways. Airways very rarely coincide with the optimum flown trajectory that the airspace user would fly. With the introduction of TBOs this restriction is removed, enabling flight-efficiency increases. However, the removal of these pre-defined structures in the ATC function requires an integrated decision process between the involved stakeholders i.e. collaborative planning.

Collaborative planning will not only be introduced at an ATC function level. In fact the main impact of collaborative planning is expected to occur through the ASM/ATFCM functions where enhanced situational awareness, supported by increased information sharing channels, will enable enhanced predictability (CHAPTER 7).

Finally, the target concept will enable a shift in the human operator role, with the ATCO assuming a more strategic activity in separating aircraft with the support of advanced automation. In the long-term, this advanced automation along with other relevant technologies will allow new separation modes, complementing or potentially replacing current ground-based separation approaches.

The ATM target concept can be explained as well in terms of the changes in functions, processes and roles.

2.5.1.1 Changes of functions

The paradigm shift in the ATM functions can be explained as a transition towards more tactical ASM/ATFCM functions and a more strategic ATC function (Ehrmanntraut and McMillan, 2007). Therefore, even though no new functions will be seen with the implementation of the ATM target concept, their performance will change. This section identifies these functional changes.
Collision avoidance

The changes in this function will be due to the enhancement of already existing technologies. SESAR will continue to introduce safety nets (*CM-0801 - Ground Based Safety Nets*). For instance, the STCA tool or the Area Proximity Warning (APW) to alert the ATCO when flights are predicted to enter protected ground areas.

TCAS will be enhanced through the introduction of OIS *CM-0802 - ACAS Resolution Advisory Downlink*, which will increase the situational awareness of the ATCO when TCAS provides resolution advisories. Similarly, *AUO-0402 - Air Traffic Situational Awareness (ATSAW) during Flight Operations (AIRB)* will contribute towards an enhanced situational awareness of the flight crew that could enhance the collision avoidance function.

ATC

The ATC function is expected to become more strategic and less tactical. This shift will be supported by enhanced predictions able to support increased awareness with larger LATs e.g. *CM-0202 - Automated Assistance to ATC Planning for Preventing Conflicts in En-Route Airspace*. This strategic shift aims to move ATCO tactical workload to a strategic workload. Strategic workload is less constraining in capacity terms as there is sufficient time prior to the execution to optimise the operations.

The ATCO will be supported by increased automation e.g. *CM-0201 - Automated Assistance to Controller for Seamless Coordination, Transfer and Dialogue*, and new communication channels (*AUO-0301 - Voice Controller-Pilot Communications (En-Route) Complemented by Data Link*) that will theoretically reduce workload compared to pre-SESAR levels. Automation will support as well the introduction of the TBO concept (*CM-0104 - Automated Controller Support for Trajectory Management*).

The increase in navigation capabilities quantified by the Required Navigation Performance (RNP) indicator, will enable the introduction of new airspace procedures such as *CM-0603 - Precision Trajectory Clearances (PTC)-2D On User Preferred Trajectories* that will make better use of the available airspace and optimise the airspace user operations.
ATC operations will be monitored and supported by new tools for the EOS, enabled by increased prediction accuracy e.g. CM-0101 - Automated Support for Traffic Load (Density) Management. This will make the traffic more predictable, hence enabling a reduction of the safety buffers used in the operations in terms of a reduction of maximum capacities (e.g. 10% capacity reduction due to traffic uncertainty) (CHAPTER 7).

Finally, the ATC function will see a major change in the long term with the introduction of new separation modes (CM-0704 - Self Separation in Mixed Mode). This change will move the ATC function from the ground to the air, where pilots will increasingly become responsible for their own separation.

**ATFCM function**

ATFCM will be more tactical with measures being applied shortly before the execution time (DCB-0205 - Short Term ATFCM Measures). In addition, enhanced predictability will reduce the amount of avoidable ATFCM regulations (e.g. ground delays) used and the effectiveness of those ATFCM measures.

*AUO-0101 - ATFM Slot Swapping* will start making the ATFCM a collaborative process in which airspace users negotiate the slots dynamically as a function of their business objectives. In the long-term, other resources of the ATM system will be negotiated by the airspace users through the *AUO-0102 - User Driven Prioritisation Process (UDPP)*.

In order to monitor the capacity/demand balance of the operational sectors, new metrics will be used, such as hourly entries and complexity (CM-0103 - Automated Support for Traffic Complexity Assessment).

**ASM function**

The ASM function will become more tactical as it happened with the ATFCM function. ASM will gradually be integrated with the ATFCM function to provide combined solutions to support air traffic operations e.g. dynamic airspace sectorisation to support ATFCM reroutings (DCB-0203 - Enhanced ASM/ATFCM Coordinated Process).
New sectorisation techniques will adapt dynamically to the existing traffic flows (AOM-0802 - Modular Sectorisation Adapted to Variations in Traffic Flows) and the civil/military requirements (AOM-0206 - Flexible Military Airspace Structures). In addition, the Functional Airspace Blocks (FABs) will eliminate cross-border boundaries and concentrate ATC activities per geographical areas, reducing the airspace fragmentation problem.

**Long-term planning function**

Network fragmentation will start to be tackled through international collaboration (AOM-0402 - Further Improvements to Route Network and Airspace incl. Cross-Border Sectorisation and Further Routeing Options). Airports will be integrated in the planning process as another stakeholder to eliminate the airspace-airport fragmentation (AO-0801 - Collaborative Airport Planning).

Capacity planning will be enhanced through a refinement process where up-to-date information will be dynamically shared until hours before the execution of the capacity plan (DCB-0201 - Interactive Network Capacity Planning). This improvement will extend the horizon of the network planning function to the pre-tactical phase and the function will be integrated with the ATFCM and ASM functions (DCB-0206 - Co-ordinated Network Management Operation extended until the Day of operation).

The target concept is captured in Figure 2-11 as a shift from the current ATM system in terms of the functions, roles and the associated time-frames.
2.5.1.2 Changes of processes

Enhanced prediction is the key element supporting the introduction of the ATM target concept and the functional changes (Schuster and Ochieng, 2011). Prediction capabilities will be enhanced by new algorithms and enhanced data (IS-0302 - Use of Aircraft Derived Data (ADD) to enhance ATM ground system performance). Prediction requirements will differ depending on the requirements for the different functions (Schuster and Ochieng, 2011)(Tobaruela et al., 2014a).

The detection processes will be enhanced through improved prediction and support tools with higher levels of automation (CM-0404 - Enhanced Tactical Conflict Detection/Resolution and Conformance & Intent Monitoring).

New resolution strategies will emerge in all the functions thanks to the new system
capabilities: navigational capabilities for the ATC function, more dynamic responses for the planning, ATFCM and ASM functions. These new resolution strategies will theoretically enable optimised operations.

In the SESAR system, information will be dynamically shared and updated by all relevant stakeholders. This will support the enhanced prediction process.

The shift will be from a point-to-point and request-based information system to a net-centric information system that will automatically request new updates when certain conditions are triggered (IS-0305 - Automatic RBT Update through TMR). This will be implemented through the so-called System Wide Information Management (SWIM) system (Figure 2-12).

Figure 2-12 System Wide Information Management (SWIM) (SESAR, 2007b)

2.5.1.3 Changes of roles

The currently existing roles in the ATM system will adapt to the new requirements introduced by the future functions. The most significant change will be incurred by the pilot, with the introduction of the self-separation mode. ATCOs will have to adapt to absorb this
change, delegating some of the air separation responsibility to the pilot.

Finally, it has been envisaged that new roles will emerge (*CM-0301 - Sector Team Operations Adapted to New Roles for Tactical and Planning Controllers*). However, the definition of these new roles has not been accomplished yet.

**Automation**

Automation will see a large expansion. As captured by many OISs, automation deployments will be seen extensively inside the operations room, fundamentally to support the ATCO. As a result, reduced tasks and workload within the ATC team will be expected (SESAR, 2007b). However, some studies (Kauppinen et al., 2002, Sollenberger et al., 2004, Metzger and Parasuraman, 2005, Endsley, 1996, Billings, 1996, Hollnagel and Woods, 2005) have already identified that the introduction of automation in the system does not always lead to lower workload and higher capacity levels. Therefore, the levels of automation introduced into the system have to be carefully defined. For example, in (Parasuraman et al., 2000) potential costs of automation that may negatively impact the system are identified: reduced situational awareness, complacency and skill degradation. In conclusion, the human is expected to have a central role in the future ATM system (Erzberger, 2001).

Human-machine interaction studies (Wing et al., 2010, Sipe and Moore, 2009) focus on determining the best functional allocation of the system. This is due to the fact that the underlying tasks of the functions can be allocated in different ways, resulting in different overall effects. While in the past automation has usually been deployed to enhance ATCO information, presentation, and integration (Voller and Low, 2004), and to automate routine tasks, current and future trends are to enhance human cognitive processes, mostly in the stage of decision selection (Willems, 2004).

Finally, automated systems will ensure interoperability to avoid system fragmentation (*IS-0301 - Interoperability between AOC and ATM Systems*).

Therefore one of the fundamental aspects in understanding the feasibility of the SESAR programme will be to assess the impacts of automation on airspace capacity.
2.6 Summary

This chapter has outlined the fundamentals of the ATM system. It has introduced the evolution of the ATM system since its origins until today. The organisation of the ATM system and its stakeholders has been detailed. In order to explain the operation of the ATM system, an approach based on functions, processes roles and time-frames has been used.

Based on this approach, the paradigm shift between today’s ATM system in Europe and the ATM target concept proposed by SESAR has been identified. The ATM target concept, which moves from an airspace based environment to a TBO environment, has been discussed, in particular its European implementation, SESAR.

The importance of enhanced prediction accuracy to allow an improved ASM/ATFCM functions performance, higher levels of automation to support ATCOs’ job and increased situational awareness by all the stakeholders have been identified as the main enablers that will support en-route airspace capacity increase.

Given that the research problem consists in assessing the feasibility of SESAR modernisation initiative in producing en-route airspace capacity increases, the next chapter will discuss further the question of airspace capacity.
CHAPTER 3 AIRSPACE CAPACITY

The objective of this chapter is to identify the main factors that affect en-route airspace capacity, together with their impact. In order to do this, this chapter initially defines en-route airspace capacity, assessing the different approaches found to describe it (Section 3.1).

A methodology for the identification of airspace capacity factors is developed and applied in Section 3.2, based on literature review, ATC sector overload reports analysis and discussions with experts.

The resulting factors are qualitatively discussed in Sections 3.3, 3.4, 3.5, 3.6, 3.7 and 3.8. In these sections it is demonstrated that the ATM system is operating below the theoretical capacity and that ATCO workload is the main en-route airspace capacity driver, although the performance of the ASM and ATFCM functions is increasingly becoming a bottleneck itself. In addition, it is found that airspace capacity cannot be understood without cost-efficiency in the current economic environment in Europe.

The characterisation of the airspace capacity drivers is fundamental to assess current airspace capacity estimation methodologies in CHAPTER 4 and subsequently propose a novel capacity estimation framework.

3.1 En-Route Airspace Capacity Definition

Capacity is the ability to contain in a volume (Simpson and Weiner, 1989), hence by extrapolation airspace capacity is the ability to contain aircraft within an airspace volume. This is a spatio-geometrical definition of airspace capacity. This approach is used by (EUROCONTROL, 2004b, Klein et al., 2008) and defines airspace capacity as the number of aircraft that can co-exist in an airspace volume given safety minima separation.

Other studies that conceive capacity as a spatio-geometrical problem introduce the concept of traffic per unit of time e.g. (Haraldsdottir et al., 1997). In this approach capacity is no longer a static characteristic of the airspace but the ability to process aircraft through time, in other words a transportation rate (Donohue, 1999). In this regard, airspace capacity is defined in...
(EUROCONTROL, 1991) defines airspace capacity as the “maximum number of aircraft going through any given geometrical airspace for a given time period, based upon the spatial control constraints that govern the internationally specified separation between any two aircraft given their performance characteristics”.

As discussed later, airspace capacity is influenced by additional factors and is not exclusively limited by spatio-geometrical constraints. Therefore, other definitions for airspace capacity arise in the literature.

In this respect, typically the ATCO has been the key limiting factor of the ATM system. For instance, (Majumdar, 2003) uses the notion of ATCO workload to define capacity. With this approach, capacity is understood to be the number of controlled aircraft that maintain ATCO task load below the maximum threshold, corresponding to controllers actively managing air traffic 70% of the time i.e. 42 minutes in an hour. Other studies (e.g. (Schmidt, 1978)) use a 80% workload threshold limit.

In this thesis, en-route airspace capacity is defined as the maximum number of aircraft that can be instantaneously controlled within safety limits. In this approach, which has been previously used in other studies (Hudgell and Gingell, 2001), capacity is not limited to either spatio-geometrical or ATCO workload factors, and can be constrained by any factor that may limit capacity.

The metric to measure capacity within this definition is the occupancy i.e. instantaneous aircraft. Occupancy has been widely used although their definitions are not consistent: occupancy is defined either as an instantaneous count of flights (Cocanower and Voss, 1998) (Klein et al., 2008) or as the number of aircraft during a given time period (Dalichampt and Plusquellec, 2007).

The occupancy is used in the US and Europe to set sector capacity thresholds. For instance, in Europe, MUAC defines the Occupancy Traffic Monitoring Value (OTMV) as the maximum number of flights in a sector during 1-minute intervals.

The OTMVs are further divided in sustained and peak OTMVs. The first is associated with a smooth flow of traffic over a long period of time, and the second with a spike of traffic that
should not be handled longer than around 3 minutes (EUROCONTROL, 2005).

In the US, the Monitor Alert Parameter (MAP) is used to declare the airspace capacity (FAA, 2012a). This has the peculiarity of being a uniform measure regardless of sector type, and is only a function of the average sector transit time, an important indicator of airspace capacity (Corker et al., 2004, Leiden et al., 2003). Occasionally it can be adjusted to account for special scenarios e.g. weather impact.

An instantaneous definition of airspace capacity as opposed to a capacity definition over a period of time (e.g. flights controlled over a 30 minutes period) allows a more precise evaluation of ATM components workload: point-in-time workload excesses can be identified rather than an aggregated view through a time interval (e.g. 30 minutes). Therefore, the instantaneous approach will be used in this thesis.

The next section identifies the factors contributing to the en-route airspace capacity.

3.2 Identification of Airspace Capacity Drivers

Operationally speaking, on the airport surface, aircraft move from the gate to the runway where flights depart and vice versa. In the TMAs, flights climb from the runway to the en-route airspace before reaching cruise altitude and vice versa. In the en-route airspace, the vast majority of traffic navigates at cruising altitude with cruising speeds that are faster compared to those in the TMA and during runway operations.

Due to these operational differences, the capacity limiting factors in the three airspace regions differ. On the airport surface, capacity is fundamentally constrained by the runway capacities (Gilbo, 1993, Weidner, 1998). Additional factors can significantly affect airport capacity, including meteorology (Klein et al., 2009), separation minima (Brooker, 1990), landside limits (stand availability) (Brooker, 1990) or ATCO workload (Montoto and Suarez, 2001). In the TMAs, the capacity has capacity features similar to that of airports, such as geometrical limitations and temporal separation between flights (Janić and Tošić, 1991) (Boswell, 1993, Robinson et al., 2002).

In general, for en-route airspace, ATCO workload is recognised in the literature as the main
capacity bottleneck, although other factors (discussed in subsequent sections) are also relevant (Neal et al., 2011). Given the thesis objectives, the research will focus exclusively on the en-route operations.

For the identification of the en-route airspace capacity factors, a template analysis methodology is used. This technique is used for qualitative research, and is based on producing a template that represents the issues identified in the textual data (King, 1998).

An initial template of operational capacity factors is drawn based on a literature review. The following step consists of producing a dedicated template for the identification of capacity limitations based on ATC sector overload reports. The results of the two templates are merged in a template that is iteratively refined, by means of discussions with SMEs leading to the final list of airspace capacity drivers. This process is depicted in Figure 3-1.

![Figure 3-1 Template analysis for airspace capacity factors identification](image)

Each of the three stages is discussed in the following three sections.
3.2.1 Literature Review

A literature review is accomplished in the first place. No literature was found specifically referring to the en-route airspace capacity limitations, therefore the initial pool of factors was derived from research studies in human factors in aviation pre-SESAR and SESAR systems. The majority of the literature assumes that the airspace limitation is already known (usually ATCO workload as it has been traditionally accepted), subsequently developing models and techniques to estimate capacity on the basis of the main limitation (i.e. ATCO workload).

The review of the studies in these themes yields five fundamental types of airspace capacity factors, which are captured in Table 3-1.

### Table 3-1 Literature review of airspace capacity factors

<table>
<thead>
<tr>
<th>Reference</th>
<th>ATCO Workload</th>
<th>Geometry</th>
<th>Weather</th>
<th>Predictability</th>
<th>Automation Workload</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>(5)</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(6)</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7)</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>(8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>

(1) (Klein et al., 2008, Krozel et al., 2007)

(2) (Andrews et al., 2005, Ruigrok et al., 2002, Janic, 2000)


(4) (Cho et al., 2011, Welch et al., 2013)
The ATCO workload group is apparent and includes any factor contributing to an increased amount of work for the ATCO.

Geometry factors include separation minima, aircraft and airspace restrictions and geometry of conflicts and traffic flows.

Weather is typically seen as an independent factor affecting airspace capacity. The severity of this factor lies in the fact that it cannot be controlled and its influence can be major, although this influence is more relevant on the airport surface.

The predictability group embeds any factor affecting the accuracy of air traffic prediction for different Look-Ahead Times (LATs). Automation workload is similar to the ATCO workload.

The findings from the literature review are complemented with insights from operational data. This is achieved through the analysis of UK’s CAA sector overload reports.

### 3.2.2 United Kingdom’s Civil Aviation Authority Sector Overload Reports

An overload is defined as an excess to information processing capacities both of perceptual and cognitive resources (Averty et al., 2003). An overload occurs when the traffic and operational conditions in the sector are such that the ATCO considers the safety of operations being comprised (Majumdar and Ochieng, 2003). An overload differs from an over-delivery as the latter only involves an overshooting of the maximum pre-defined capacity, which does not necessarily involve an excess of human processing capabilities.

When an overload occurs the capacity threshold of the ATCO has been exceeded. Therefore,
sector overload reports are seen as a unique source for identifying airspace capacity factors within the ATCO workload bottleneck.

The overload reports chosen are those from the UK’s CAA. These reports, integrated into the UK’s CAA Mandatory Occurrence Reporting (MOR) scheme (CAA, 2011) collected by the Safety Investigation and Data Department, are completed by ATCOs in circumstances matching the CAA specifications for reporting. An overload report records in essence the conditions that led to the overload from the ATCO perspective, how it built up and how it developed. An example of a UK’s CAA MOR sector overload can be found in Appendix 3.

A total of 179 reports were analysed covering the period between 2002 and 2010 for the London Area Control Centre (LACC), which controls the en-route traffic within the London Flight Information Region (FIR).

### 3.2.2.1 Overload reports capacity factors

Based upon the initial template created from the literature review together with a detailed reading of the narratives of the reports, a dedicated template is developed to analyse these reports. This template is formed of the factors shown in Table 3-2.
Table 3-2 Dedicated sector overload template

<table>
<thead>
<tr>
<th>Factor Groups</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrong Situational Awareness</td>
<td>Misunderstandings, incorrect mental pictures or unawareness of events and notices.</td>
</tr>
<tr>
<td>Air traffic complexity</td>
<td>Traffic pattern (e.g. traffic bunching), bad weather or emergency traffic.</td>
</tr>
<tr>
<td>Equipment</td>
<td>Failure, user unfriendly or wrong use.</td>
</tr>
<tr>
<td>Staffing</td>
<td>Insufficient ATCOs or not in position.</td>
</tr>
<tr>
<td>Abnormal scenarios</td>
<td>Events, new procedures, tools or airspace configuration</td>
</tr>
<tr>
<td>Capacity management</td>
<td>ASM/ATFCM measures performance.</td>
</tr>
<tr>
<td>ATC teamwork</td>
<td>Inability to conduct tasks or wrong task performance.</td>
</tr>
<tr>
<td>Radio communications</td>
<td>High amount, poor quality or extensive ones.</td>
</tr>
<tr>
<td>Predictions / adherence</td>
<td>Inaccurate traffic load prediction, bad interpretation, poor flight plan compliance or weather prediction.</td>
</tr>
<tr>
<td>Coordination</td>
<td>Compliance with established agreements, amount of non-agreed coordination or military coordination.</td>
</tr>
<tr>
<td>Individual differences</td>
<td>Training and experience.</td>
</tr>
</tbody>
</table>
The factor groups in Table 3-2 are identified after the first iteration of evaluation of the reports. Following the choice of factor groups, the next iteration consists in the identification of existing factors groups in each overload report. This mapping of factor groups may result in multiple simultaneous factors groups for a single report.

Table 3-3 shows the results of the factor group identification. Over the nine years, airspace complexity is clearly the main contributor of sector overloads, therefore empirically corroborating previous research (Mogford et al., 1995). Prediction, mostly referring to traffic load and complexity prediction is also an important contributor. The accuracy of the prediction of the traffic and weather is of paramount importance in building the situational awareness of the ATCO. When these predictions are inaccurate ATCOs are ill-prepared to handle the situation. For example, (Kallus et al., 1997) identifies this as a mismatch between the mental model and mental picture.

![Table 3-3 Sector overload factors histogram](image)

Table 3-3 Sector overload factors histogram

Staffing and capacity management are secondary contributors are seen in Table 3-3. The former refers to the availability of ATCOs to staff operational sectors. In fact, if there are no available ATCOs, fewer operational sectors will be open with a consequent reduction of airspace capacity.
The latter refers to the performance of the ASM/ATFCM functions in ensuring that ATCO workload levels are maintained within safety limits through the measures implemented by these functions.

Although the relevance of these two drivers is not as significant as in other factors, their increasing importance is recognised during the SME discussions stage.

3.2.3 Subject Matter Expert discussions

In order to refine the pool of factors and corroborate the identified factors through the literature review and the UK’s CAA sector overload reports analysis, SMEs were interviewed to identify and verify these factors. Semi-structured interviews were conducted with SMEs from the main ANSPs in the European core area including:

- NATS (U.K.);
- AENA (Spain);
- DFS (Germany);
- DSNA (France);
- Skyguide (Switzerland);
- EUROCONTROL Maastricht Upper Area Control (Netherlands, Belgium, Luxembourg and West-Germany upper airspace);
- EUROCONTROL (much of the rest of the Europe).

Furthermore, experts from industry and academia were also interviewed including at:

- Imperial College London (UK);
- University Polytechnic Madrid (Spain);
- Deep Blue (Italy);
- NLR (The Netherlands)
- CRIDA (Spain).

The objectives of these interviews were to identify:

- Current factors that affect airspace capacity based on the knowledge of the SME on
the ATM system;

- Future factors that will affect airspace capacity due to the implementation of new initiatives, and based on the SME’s experience from past implementations or on the knowledge about the ATM system;

- General comments and recommendations on the already identified factors from the literature review and the UK’s CAA sector overload reports.

All SMEs had more than 10 years of experience in the ATM domain and were either operational staff (e.g. ATCOs) or engineers involved with the technical systems at the ATC centres. In particular, they were chosen to elicit their knowledge on the implementation of new concepts in their respective ATC centres.

During the interviews SMEs were firstly walked through to the three objectives of the discussions in order to narrow the scope of the discussion. Afterwards they were introduced to the pool of factors. The latest available pool of factor was used in these discussions i.e. the SMEs did not use the same pool of factors for the discussion but the one resulting from the prior SME discussion. In this manner, the pool of factors was iteratively refined by SMEs whilst the interviewer (the author of this thesis) ensured global pool consistency and comprehensiveness e.g. avoiding duplication of factors due to different SMEs using different terminologies.

The results of these discussions concluded that the airspace capacity factors can be described in terms of a taxonomy including six fundamental categories:

1. Spatio-geometrical limitations (Section 3.3)
2. ATCO workload limitations (Section 3.4)
3. ASM and ATFCM functions performance: predictability limitations (Section 3.5)
4. Cost-efficiency limitations (Section 3.6)
5. Automation workload (Section 3.7)
6. Other factors (Section 3.8)

These are discussed hereafter. The SMEs agreed that in the long-term and if the rest of restrictions imposed by the other capacity factors groups are overcome, spatio-geometrical limitations would become the main capacity restriction.
In addition, spatio-geometrical factors can result being the underlying driver to ATCO workload. For instance, in convergent air traffic flows (e.g. arrivals to an airport), sequencing and merging traffic harmonisation strategies are needed as the airport runway can only accept one aircraft at a time with a given time interval between successive aircraft. This is in essence a spatio-geometrical problem that in turn generated additional workload for the ATCO.

ATCO and automation workload have similar characteristics (Tobaruela et al., 2012). In fact, these two groups embed all those factors that can limit capacity due to insufficient capabilities to process information. A distinction is made between the saturation of a human operator (ATCO or pilot) and an automated system.

In the current ATM system, the ATCO is expected to be the key limiting element for capacity. The pilot and automation can potentially become limiting factors in long-term scenarios. For instance, the increased responsibility of the pilot and the airborne systems as a result of delegation of separation to the air crew (SESAR, 2008c) can turn into a saturation of these two elements.

The SMEs identified that ASM and ATFCM functions are the main enablers for maintaining ATCO workload below thresholds and it was pointed out that the performance of these functions can constitute a bottleneck itself. In fact, a flawed performance can be managed by the EOS inside the operations room, by taking protective measures (e.g. lowering declared capacities), hence reducing the available capacity. The performance of these functions is fundamentally driven by their ability to predict air traffic demand i.e. predictability.

Finally and as already identified in Section 3.2.2, SMEs recognised that airspace capacity can be achieved at the expense of an intensive use of resources i.e. ATCOs. However, this penalises on the ATC centres cost-efficiency since ATCOs are expensive resources. Therefore, the performance of the planning function and its effect on cost-efficiency is recognised to be a factor affecting en-route airspace capacity.

The sections below explain each of the capacity factor groups in further detail and discuss their relative importance.
3.3 Spatio-Geometrical Limitations: Theoretical Capacity

Similar to other means of transport such as road and maritime, the capacity of the ATM system is theoretically bounded by the separation standards in effect for the given airspace. This capacity concept is referred to in this thesis as theoretical capacity although it has been named differently in prior literature e.g. inherent capacity (Andrews et al., 2005).

Typically, spatio-geometrical saturation occurs on the airport surface i.e. stands, apron, taxiways and runways. It also occurs in the TMAs during the approach phase, in which aircraft are placed in sequence in preparation for landing on the runway (Boswell, 1993). In the en-route domain, spatio-geometrical saturation is rarely reported and no literature has been found dealing specifically with this issue. Nevertheless, whilst demand increases, the amount of spare space decreases, leading to potential spatio-geometrical saturation.

3.3.1 Separation standards

Aircraft flying through controlled airspace are assigned a fixed amount of lateral and vertical space defined by the separation standards. During the period of time that a volume of space is used by an aircraft, none other is allowed to penetrate this volume. Hence, the smaller the separation standards, the more aircraft can be fitted into a given airspace volume. Separation standards are dictated by each national authority although they usually follow the provisions in (ICAO, 2007). Variations to these are captured in the national Aeronautical Information Publication (AIP) bulletins.

In en-route airspace, ICAO indicates 5 Nm of horizontal separation and 1000 feet of vertical separation below Flight Level (FL) 290 and 2000 feet above FL 290. In Reduced Vertical Separation Minima (RVSM) airspace the vertical separation is 1000 feet throughout (Figure 3-2). RVSM airspace was introduced in Europe on 24 January 2002 between Flight Levels 290 and 410 inclusive (JAA, 1999). This change enabled doubling the amount of flight levels. In some scenarios, such as small airspace sectors in the presence of bad weather or active military areas, RVSM has enabled reducing the spatio-geometrical constraint. Additionally, it has increased the efficiency of the airborne operation since aircraft can fly closer to their optimal flight level.
(Thompson, 1997) reviews the history of the development of airspace separation standards and states that the standards for radar-controlled airspace have evolved slowly and are not based on a formal model of collision risk. (Rockman, 1994) states that the 5 Nm separation is due to the larger arcs shown in the radar display for flight trajectories distant from the physical radar location. Due to this visualisation issue, a 5 Nm was agreed as a safe separation to differentiate between flights.

The separation established between traffic accounts for navigation performance, aircraft exposure to other traffic (i.e. spatio-geometrical airspace consumption including wake vortex separations) and the capabilities of the ATC system to assure separation (ICAO, 1999).

3.3.1.1 Navigation performance

In the navigational domain, performance standards are developed locally in order to operate within the airspace. The different navigation standards are captured in a metric that shows the accuracy of the aircraft navigation called Required Navigation Performance (RNP). Table 3-4 shows the different RNP standards used in today’s ATM system.
Table 3-4 RNP classification (ICAO, 1999)

<table>
<thead>
<tr>
<th>RNP Type</th>
<th>1</th>
<th>4</th>
<th>10</th>
<th>12.6</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (Nm)</td>
<td>+/- 1.0</td>
<td>+/- 4.0</td>
<td>+/- 10</td>
<td>+/- 12.6</td>
<td>+/- 20</td>
</tr>
</tbody>
</table>

Increased navigation accuracy (reduced RNP) can enhance airspace capacity through the creation of new procedures e.g. point merge (Favennec et al., 2010) and the creation of new routes, which are not restricted to flying over physical navigation aids and can therefore alleviate the congestion of existing routes e.g. RNAV (Robinson et al., 2002).

Table 3-5 shows the effects of increased navigation performance (RNP) on the reduction of separation standards based on a review of literature in navigation performance and separation standards.

Table 3-5 Relationship between RNP and lateral separation minima

<table>
<thead>
<tr>
<th>RNP</th>
<th>Lateral separation minima (Nm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>100</td>
<td>ICAO</td>
</tr>
<tr>
<td>12.6</td>
<td>60</td>
<td>(FAA, 2012b)</td>
</tr>
<tr>
<td>10 (+ CDPLC)</td>
<td>50</td>
<td>(FAA, 2005b)</td>
</tr>
<tr>
<td>4 (Radar)</td>
<td>5</td>
<td>(ICAO, 1999)</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>(Haraldsdottir et al., 1997)</td>
</tr>
<tr>
<td>4 + containment$^1$</td>
<td>14</td>
<td>(Haraldsdottir et al., 1997)</td>
</tr>
<tr>
<td>4 (including CDPLC)</td>
<td>30</td>
<td>(FAA, 2005a)</td>
</tr>
</tbody>
</table>

These results are depicted in Figure 3-3. In this graph two curve behaviours can be distinguished:

- One behaviour in which navigation accuracy is inversely proportional to lateral separation minima. This result is expected as increased accuracy should reduce

$^1$ The containment region identifies the volume in which the aircraft is 99.9999% of the time.
separation requirements.

- Another behaviour in which the lateral separation minima is not a function of navigational capabilities i.e. RNP. This result shows that above a given RNP (between RNP 4 and RNP 10 for the current ATM system), the separation standards are no longer a function of navigational capabilities and depend on other factors: ATC capabilities (e.g. ATCO reaction time) and aircraft exposure.

Figure 3-3 Lateral separation minima standards as a function of navigation accuracy

3.3.1.2 ATC capabilities

In procedural environments such as oceanic airspace, where ATCOs are not directly involved in the separation task due to lack of radar coverage, navigation performance factors are predominant. On the other hand, in en-route environments the ATC system gains more importance due to the important role assumed by the ATCOs and ATC systems in the execution of the ATC function.

Even when the navigation performance of the air traffic is very accurate, the ATC function still needs to be precisely informed of the positions and intentions of the aircraft to ensure that separation is being maintained. Therefore, enhanced positioning and surveillance capabilities can reduce separation standards (Kostiuk and Lee, 1997). Primary and secondary radars are used in the current ATM system for surveillance purposes and ADS-B is expected
to be implemented in the future. The higher accuracy of navigation systems together with increased reliability of communication systems enables higher accuracy surveillance systems such as ADS-B.

Nevertheless, position accuracy of the air traffic is not the only factor driving the ATC capabilities. When a loss of separation is predicted to occur, the system needs to react in time. Reaction times are dependent on (ICAO, 1998):

- Surveillance system reaction time: for en-route radar, the update rate is every 12 seconds (ICAO, 2012)
- ATCO reaction time, dependent on cognitive skills and automated system support.
- ATCO/pilot communication performance.
- Pilot and aircraft response time.

Therefore, the inherent time in the successive steps for the determination of a LOS is translated into a minimum separation requirements between aircraft to avoid potential collisions. The introduction of automated messaging between ground and air (CPDLC) can enable a reduction of the reaction times and hence the minimum separation requirements.

3.3.1.3 Aircraft exposure

The separation standards are influenced by the likelihood of traffic encountering other aircraft. This is fundamentally determined by the airspace structure including traffic complexity, routes structure and traffic demand pattern (ICAO, 1998). The larger is the exposure of the flights between them the higher the probability of encounter.

(Jing and Zhang, 2010) perform an analysis of the separation minima requirements based on a given airspace structure, showing that separation standards due to aircraft exposure factors can be reduced by increased navigational accuracy.

3.3.2 Airspace user preferences

Commercial airlines intend to maximise profit and in doing so they offer routes and schedules tailored to passenger preferences. Financial incentives such as taxing policies for airports and
airspace can drive airspace user preferences (Robyn, 2007). As a result and due to the presence of network effects that influence air traffic demand (Fangqin and Minghua, 2009), certain airports and routes are congested during certain periods of time. For example, traffic follows seasonal trends during the day, during the week and during the year.

Figure 3-4 Daily traffic evolution for ESRA flights (data extracted from EUROCONTROL STATFOR portal)

Figure 3-4 shows the seasonality of the traffic for the Eurocontrol Statistical Reference Area (ESRA). During the summer period, traffic rises with a typical double peak during July and September and drops during winter, especially during the Christmas holidays period. In order to see the weekly variations, Figure 3-5 zooms in on the region enclosed by the rectangle in Figure 3-4.
Figure 3-5 shows the lower traffic during weekends (especially on Saturdays). Friday is the busiest day and the peaks occur on the first day of each month.

Traffic in airports is scheduled to concentrate arrivals/departures during certain time periods, so that airlines can make optimal use of resources and allow for passengers flight connections (Kösters, 2007). The evolution of aircraft movements for example for Munich airport as a function of time is shown in Figure 3-6.
In addition, European air routes in the en-route domain are structured in terms of airways. An airway is a set of concatenated geographical coordinates for a given flight level. These airways reduce the flexibility of airspace users to fly their preferred routes and concentrate the traffic along them, thereby preventing optimal use of the available airspace. Even when the airspace user is not tied to follow rigid airways, traffic shows that the preferred trajectories concentrate in certain regions of airspace, with the remaining airspace underutilised. In fact, there is a limit to the extent to which flights can select sub-optimal trajectories to avoid congestion. This limit is the efficiency of the operation.

Therefore, even in the ideal case of a free route environment, concentration of traffic in certain areas occurs, even when other available airspace is not saturated.

### 3.3.3 Airspace availability

Finally, the spatio-geometrical limitation is bounded by the actual amount of airspace available. Not all the airspace can be used for commercial operations due to the presence of other stakeholders (e.g. military users), the presence of weather (e.g. storms) and the existence of reserved volumes of airspace were commercial aviation is not allowed to fly through, for instance due to environmental restrictions.

### 3.3.4 Maximum spatio-geometrical capacity: The circle packing problem

This section calculates maximum capacity of the airspace assuming only a spatio-geometrical limitation i.e. the theoretical capacity. This calculation is compared with actual traffic in European airspace, thus enabling to conclude whether current traffic levels are bounded by spatio-geometrical limitations.

The theoretical capacity has traditionally been overlooked for en-route airspace apart from a few studies. (Ruigrok et al., 2002) calculate the two-dimensional capacity based on the space consumption for each flight (5 Nm around each aircraft). A more recent study by (Andrews et al., 2005) calculate the so-called inherent capacity of the airspace by cloning aircraft trajectories until airspace is saturated (density threshold is set for trajectories crossing with less than 8 Nm separation). (Krozel et al., 2007, Klein et al., 2008) approach the calculation through flow theory, capturing the effects of weather blockage in the spatio-geometrical
capacity.

In this section the spatio-geometrical capacity is computed following the (Ruigrok et al., 2002) approach. The results are then compared with the actual maximum density that can be reached in the MUAC en-route airspace. The following assumptions are applied in the calculation:

- Free-route airspace: it is assumed that aircraft can occupy any portion of airspace and are not restricted to fixed airways. This is in fact, the case for MUAC airspace.
- Static conditions: the relative movement between aircraft is zero: equal velocity vector (magnitude and direction). This makes optimal use of available airspace. In reality, speeds and directions of flights within an airspace differ, thus leading to reduced theoretical capacities. However, this case study aims to calculate the maximum possible theoretical capacity, therefore this assumption is consistent.
- Horizontal separation between aircraft: $H_S$ (5 Nm en-route European airspace). If the airspace is much bigger than the circle area around each flight (no-entry circle), then the corners of the airspace can be dismissed. Otherwise if the area has the same order of magnitude the relative position and diameter of the circle would significantly change the density (Peikert, 1994).

Since horizontal separation is omnidirectional each flight is surrounded by a no-entry circle of 5 Nm. According to Thue’s theorem (1892), circles in a Euclidian plane are packed with the highest density (~0.9069 of area covered by circles) with the hexagonal packing lattice (Fukshansky, 2011). This is known as the circle packing problem (see Figure 3-7).

![Figure 3-7 Hexagonal circles lattice (Fukshansky, 2011)]
Assuming an airspace of characteristic side length $L \gg H_S$ (see Figure 3-7), the density of each FL is approximated by:

$$Density_{per\ FL} = \frac{\text{capacity}}{\text{area}} = \frac{L}{2H_S^2} \frac{L}{2H_S \cos \frac{\pi}{6}} \sqrt{\frac{1}{L^2}} = \frac{1}{2\sqrt{3}H_S^2} \quad [3-1]$$

As seen in the equation above, density follows a hyperbolic function with vertical asymptote tending to $\infty$ when $H_S \rightarrow 0$.

Given the assumptions introduced previously in the section, the density per FL is solely a function of $H_S$ [3-1]. The maximum spatio-geometrical density in oceanic airspace, where separation minima are 60 Nm for aircraft (FAA, 2012b) is $2.34e-05$ flights/Km$^2$ per FL, whereas in en-route airspace it is $3.37e-03$ flights/Km$^2$ per FL. These densities are calculated per unit of area and FL. The theoretical capacity of an airspace volume for en-route airspace ($H_S=5$ Nm) corresponds to equation [3-2]:

$$Theoretical\ Capacity = 1.3466E - 02 \times \text{area} \times \text{flight\ levels} \quad [3-2]$$

The theoretical capacity is compared to actual air traffic demand figures in MUAC aerospace in the paragraphs below.

For each operational sector in MUAC, Table 3-6 calculates the actual air traffic densities when the air traffic demand equals the declared capacity of the operational sectors. The calculation of the airspace volume for upper sectors (FL>335 in Hannover and FL>345 in the DECO and Brussels sector group) is complex as it is limited not geometrically (e.g. an airspace boundary) but by aircraft performance (i.e. aircraft ceiling). The optimum FL of commercial aircraft, which is a function of its aerodynamics, thrust, weight and atmospheric conditions, is typically below 40,000 feet. Therefore, the exact upper boundary cannot easily be determined. In order to avoid this, the densities are calculated only for lower sectors in which the upper and lower boundaries are exactly defined (see second and fourth columns in Table 3-6).
<table>
<thead>
<tr>
<th>Sector group</th>
<th>Flight Levels</th>
<th>Operational Sector</th>
<th>Area (km²)</th>
<th>Declared capacity (flights)</th>
<th>Theoretical capacity</th>
<th>Maximum density (flights/Km² FL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brussels</td>
<td>245-335 (9)</td>
<td>EBMAWLSL</td>
<td>25229</td>
<td>12</td>
<td>764</td>
<td>5.28492E-05</td>
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<td></td>
<td></td>
<td>EBMABEL</td>
<td>23918</td>
<td>11</td>
<td>724</td>
<td>5.11005E-05</td>
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<td></td>
<td></td>
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<td>10653</td>
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<tr>
<td></td>
<td></td>
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<td>13265</td>
<td>10</td>
<td>402</td>
<td>8.37626E-05</td>
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<tr>
<td></td>
<td></td>
<td>EBMKOL</td>
<td>11735</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>EBMANIL</td>
<td>13494</td>
<td>10</td>
<td>409</td>
<td>8.23411E-05</td>
</tr>
<tr>
<td>DECO</td>
<td>245-345 (10)</td>
<td>EHDELLO</td>
<td>48744</td>
<td>15</td>
<td>1641</td>
<td>3.0773E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EDYJHLO</td>
<td>94909</td>
<td>18</td>
<td>3195</td>
<td>1.89655E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EDYJELO</td>
<td>62571</td>
<td>15</td>
<td>2107</td>
<td>2.39728E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EDYHOLO</td>
<td>32338</td>
<td>15</td>
<td>1089</td>
<td>4.63851E-05</td>
</tr>
<tr>
<td>Hannover</td>
<td>245-335 (9)</td>
<td>EDYYHLW</td>
<td>36136</td>
<td>10</td>
<td>1095</td>
<td>3.0748E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EDYHYLE</td>
<td>33202</td>
<td>12</td>
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<tr>
<td></td>
<td></td>
<td>EDYCELO</td>
<td>17686</td>
<td>12</td>
<td>536</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>EDYRILO</td>
<td>14233</td>
<td>10</td>
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<td>EDYMNLO</td>
<td>21903</td>
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<td>6.08745E-05</td>
</tr>
</tbody>
</table>

The theoretical capacity is 2 orders of magnitude larger than its associated declared capacity, as identified in other studies e.g. (Donohue, 1999).

The difference between theoretical capacity and the actual air traffic demand in European airspace demonstrates that in the current ATM system, during maximum capacity periods the airspace is not spatio-geometrically saturated i.e. there is space available for additional air traffic.

Table 3-6 additionally calculates the maximum density for traffic levels at the declared capacity for each operational sector:

\[
\text{Maximum Density} = \frac{\text{Declared Capacity}}{\text{Sector Area} \times \text{Available Flight Levels}} \left(\frac{\text{flights}}{\text{km}² \text{ FL}}\right) \quad [3-3]
\]

The calculated maximum density column shows the relationship between the size of the
operational sector and aircraft density, depicted in Figure 3-8. It can be observed that increased size of operational sectors lead to reduced aircraft density. Equation [3-4] shows this functional relationship (R-square value of 0.9794).

\[
\text{Actual Density} = \frac{1.009e5 \cdot area^2 + 1.007 \cdot area + 0.2512}{area^2 + 0.3635 \cdot area + 0.4733}
\]  

[3-4]

In small size operational sectors, the actual air traffic density is closest to the one limited by spatio-geometrical constraints. In large operational sectors the difference between the theoretical capacity and the declared capacity is even larger.

The inverse relationship [3-4] which shows a reduction of the maximum air traffic density as sector size increases is due to two factors:

- ATCO workload is increased, relative to small sectors, due to the increase of coordination workload generated by larger amounts of traffic (Welch et al., 2007). It is generally accepted that ATCO workload increases as a quadratic function of air traffic (EUROCONTROL).

- Airspace user preferences (Section 3.3.2): traffic generally tends to concentrate in certain regions of airspace. This makes some airspace volumes underused, although they are available. In smaller sectors a larger proportion of airspace volume generally correspond to the desired volumes to be flown by the airspace users. Airspace users will decide to fly through underused volumes only if the relative cost of an additional mile increases operational efficiency e.g. delay avoidance (Cook et al., 2004).

This section has shown that in the current ATM system capacity is not limited by spatio-geometrical constraints as other research had previously stated (Andrews et al., 2005, Welch et al., 2007, Karl et al., 1996).
3.4 Air Traffic Controller Workload

The previous section has shown that capacity is not spatio-geometrically limited. Other factors are more relevant, especially ATCO workload (Majumdar, 2003, Andrews et al., 2005). In many safety risk industries like ATC, workload is a main concern since any overload can potentially be detrimental for the safety of the operations. Research showing this effect has been accomplished in domains such as piloting (McCracken and Aldrich, 1984), military command and control (Gregoriades and Sutcliffe, 2006), surgery (Norman et al., 1991), road driving (Benedetto et al., 2011) or railway signalling (Pickup et al., 2010).

Even though there is no agreement on a single definition for human workload (Averty et al., 2003), most authors agree that workload represents the cost or effort of accomplishing a set of tasks i.e. the task load (Hart and Wickens, 1990, Majumdar et al., 2005, Tobaruela et al., 2014b).

Some studies (Pawlak et al., 1996) distinguish between mental and physical workload (the
latter being associated with the physical actions performed), this cost usually represents a psychological or mental state (Hart and Staveland, 1988, Tattersall and Foord, 1996). This mental state varies amongst individual operators and is relative to the individual operating skills of each operator (Hopkin, 1995) i.e. a given task load produces different workload levels across different operators. Therefore, workload is subjective and associated to each human operator and task load.

Workload is a key factor limiting airspace capacity since excessive demand on the ATCOs can lead to operational errors (Majumdar, 2003). An operational error in an en-route context is defined as an occurrence resulting in a separation between two or more aircraft lower than the applicable separation minima (FAA, 2002). Operational errors are therefore used as primary safety indicators (Bailey, 2012). Operational errors originating from the human are known as human errors and can be caused by excessive workload (Reason, 1990). Workload affects an effective decision-making process by means of reducing the ability to attend, analyse and act upon information, and can therefore directly impact safety (NLR, 2002a).

Dedicated research has focused on identifying the cognitive processes leading to human errors (Reason, 1990, Hollnagel, 1998, Bisseret, 1971):

- Incorrect perception.
- Incorrect mental picture or alteration of reality.
- Incorrect action execution or lack of precision.

Nevertheless, these errors cannot be solely attributed to excessive workload. Research has shown that sustained periods of extremely low (Dunn and Williamson, 2012) workload can also lead to a degraded cognitive performance. Such periods are fundamentally caused by the presence of very low air traffic demand, and are operationally prevented through the introduction of visual advisories and other means of increasing ATCO attention.

On the other hand, excessive workload periods are prevented through the introduction of techniques to better handle such air traffic scenarios to reduce workload below safe margins. Such techniques include:

- General procedures to ensure that air traffic follows given standards for which the
ATCO is prepared (e.g. Letters of Agreement (LoAs) between adjacent centres and demand protection measures through ASM/ATFCM functions).

- Specific training and working practices to ensure that the ATCOs are duly prepared to safely control given air traffic scenarios even in the presence of abnormal situations e.g. system failure or air traffic over-delivery.

From a capacity perspective, the focus should be on the periods of high workload, which are caused by high air traffic demand.

Workload can be further described in terms of a set objective and quantifiable factors not dependent on the individual ATCO perception i.e. the objective complexity.

### 3.4.1 Objective complexity

The term complexity was used for the first time in (Schmidt, 1976) to refer to the level of difficulty of the ATCO job. The air traffic complexity is the main contributor to ATCO workload along with the psychological state of the ATCO (Averty et al., 2003, Djokic et al., 2010). In general terms, the more difficult the task, the more complex the mental operations and the more mental processing power and capacity is used. Under these circumstances, the human tends to experience higher workload levels.

Complexity can be divided into objective complexity and perceived complexity (Li and Wieringa, 2000). The former embeds the quantifiable and observable factors of the air traffic situation, whereas the latter accounts for subjective perception of each ATCO of the objective complexity factors. However, most of the literature does not account for this distinction. The failure to capture the perceived complexity is because most studies do not intend to capture individual differences across ATCOs. In these cases the term complexity refers to the so-called objective complexity.

Due to the relationship between objective complexity and ATCO workload, several studies have attempted to find the most important objective complexity factors (Christien and Benkouar, 2003, Majumdar and Ochieng, 2007, EUROCONTROL, 2006, Sridhar et al., 1998) affecting the current ATCO activities and even those envisaged in the future (Kopardekar et al., 2008a).
The objective complexity factors belong to one of the following groups: air traffic scenario complexity, structural complexity and system complexity.

### 3.4.1.1 Air traffic complexity

The air traffic scenario complexity encompasses air traffic pattern factors (Sridhar et al., 1998) and other operational air traffic scenario characteristics such as the weather and the number of special flights and emergencies (Kopardekar and Magyarits, 2003, Inc., 1996, Mogford et al., 1995).

Regarding the air traffic pattern factors, Table 3-7 reviews the most representative factor groups found in the relevant literature.
<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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</thead>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
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<td><strong>Conflict time-to-go</strong></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Flights in holdings</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td><strong>Transit time</strong></td>
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<tr>
<td><strong>Knowledge of the intent</strong></td>
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<td><strong>Proximity to boundary</strong></td>
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</table>

Table 3-7 Air traffic pattern complexity factors
References for Table 3-7:

1. (Terzioski et al., 2012)
2. (Kopardekar et al., 2008a)
3. (Chatterji et al., 2008)
4. (Gianazza et al., 2009)
5. Complexity metrics for FASTI
6. (Christien and Benkouar, 2003)
7. (Mogford et al., 1994)
8. (Inc., 1996)
9. (Djokic et al., 2010)
10. (Flynn et al., 2006)
11. (Hilburn, 2004)
12. (Manning and Pfleiderer, 2006)

It can be observed in this table that the most cited air traffic complexity factor is the occupancy of the airspace sectors. However, the air traffic complexity of airspace sectors with the same occupancies can significantly differ based on the actual distribution of the flights present in the airspace sector i.e. what is the performance of the difference flights (aircraft mix, distribution of routes, altitudes and speeds), their transit time through the airspace sector and the proximity to the sector boundaries and the level of coordination required.

One of the most significant features that define the complexity of the distribution of air traffic, which affect air traffic complexity and subsequently ATCO workload, is the number of flights in evolution (ascending/descending). Higher number of flights in evolution lead to increased ATCO workload, since flights tend to be less predictable when ascending/descending (less flight intent knowledge) and the air traffic separation task turns to be 3-dimensional instead of 2-dimensional for horizontal performance (increased conflict geometry complexity).

3.4.1.2 Structural complexity

The structural complexity represents the objective complexity associated with stationary
airspace factors such as the airspace sectorisation characteristics and network of routes i.e. the airspace design (Arad, 1964, Stein, 1985, Sridhar et al., 1998). Structural complexity factors encompass special use of airspace, sector geometry, sector size, requirements for lateral and longitudinal separation, radar coverage, the number of FLs available (Kopardekar and Magyarits, 2003, Inc., 1996).

Structural complexity factors are of paramount importance in the generation of ATCO workload and in the air traffic complexity factors discussed in the previous section. (Buckley et al., 1983) find a correlation between the structural and air traffic complexity factors, suggesting that an adequate airspace design decreases the difficulty associated with controlling the air traffic pattern.

The structural complexity factors are uniquely associated with each individual airspace. Therefore, the objective complexity factors associated with different airspaces are not transferable between them (Christien and Benkouar, 2003, Tobaruela et al., 2014b).

3.4.1.3 System complexity

The ATC system complexity (or cognitive complexity (Cummings and Tsonis, 2006)) is the difficulty associated with the operation of the ATC systems (Histon and Hansman, 2002). Archaic ATC systems lead to higher system complexity than modern ATC systems, thus increasing workload (Kopardekar and Magyarits, 2003). The system complexity also includes eventual scenarios such as poor communications quality or ATC system failures.

Therefore, objective complexity depends on the instantaneous air traffic scenario, the eventualities of the real operations (weather and quality of equipment) and the static structural factors of the airspace in control. The same combination of these factors can however produce different perceived complexities, and subsequently workload levels, by different ATCOs. This is due to the differences and subjectivities of the ATCOs cognitive processes.
3.4.2 ATCO cognitive processes

The objective air traffic scenario is controlled by the ATCO in three fundamental cognitive processes (Dehn et al., 2007, Parasuraman et al., 2000):

- Information acquisition and analysis
- Decision and action selection
- Action execution

The three cognitive stages are differently performed by individual operators due to their individual differences. These differences include (Hart and Staveland, 1988, Kallus et al., 1997):

- ATCO skills
  - Sensory/motor skills
  - Cognitive skills
  - Knowledge base
- ATCO conditions
  - Age and experience (Rothaug, 2003)
  - Emotional state
  - Anxiety (Collins, 1992)
  - Fatigue (including type of shift and worked hours)
- Ergonomic factors (e.g. temperature and illumination)
- Teamwork

The following sections introduce each of the cognitive stages in detail.

3.4.2.1 Information acquisition and analysis

The activities developed by the ATCO are commanded by a cognitive structure called the mental model. The mental model can be described as the human representation of a system, which enables making predictions and taking actions to drive the system performance (Rouse and Morris, 1986).
The instantaneous representation of the reality based on external stimulus and perceptions and their projection into the future configures the mental picture (Endsley, 1988). As long as the mental picture corresponds to the dynamic external environmental inputs received, the ATCO is maintaining situational awareness (Kallus et al., 1997). Situational awareness is therefore the perception and integration of environmental information with the previous knowledge (mental model) of the system to develop a mental picture that can be used to predict future system status.

The successful accomplishment of the ATCO goals relies on maintaining the situational awareness. This is ensured fundamentally through an adequate training associated with the ATC system, procedures of the airspace and traffic to be controlled and adequate workload levels throughout the ATC activity (CHAPTER 3).

During the information acquisition stage, the ATCO gathers the information provided by the different resources (Section 2.3.6.1). This information, which is communicated by automated systems or other humans, is acquired through one of the following human cognitive channels: visual or auditory. Once the information is gathered, it is stored in the ATCO cognitive resources, in the so-called short-term memory (Atkinson and Shiffrin, 1968). This perceptual information is subsequently processed into a representation of the reality, the mental picture (Section 2.3.6.1), and stored in the working memory (Baddeley and Hitch, 1974). The working memory is a low capacity memory, thus it represents the main bottleneck of the human cognitive system (Kallus et al., 1997).

The mental picture is associated with a perceived complexity level (Pawlak et al., 1996), which differs from the objective complexity due to the subjectivity introduced by the ATCO perception and mental representation of the reality. Based on the information gathered in the working memory and its perceived complexity, the ATCO evaluates a decision to be made. The decision-making process is based on the application of previously acquired knowledge i.e. the mental model (Section 2.3.6.1). This previous knowledge is stored in the long-term memory and includes language and rule-based knowledge, and specific knowledge on particular scenarios based on experience (EUROCONTROL, 1996). The three cognitive memories and their relationships are depicted in Figure 3-9.
Based on the human interpretation of the real air traffic scenario, the ATCO detects that actions are needed to meet the ATC objectives and decides on which actions are required i.e. the decision and action selection stage.

### 3.4.2.2 Decision and action selection

The aim of the decision and action selection stage is to elaborate a strategy to manage the air traffic scenario represented by the mental picture and its associated perceived complexity (Mogford et al., 1995, Sperandio, 1978). This strategy is expressed in a set of tasks or task load. Whilst workload is the “subjective demand experienced in the performance of a task”, task load is the “objective demands of a task” (Hilburn, 2004). During the strategy selection process, cognitive resources are dynamically allocated in a prioritisation process, in order to place more effort on accomplishing the primary goals (Robert and Hockey, 1997).

The task load ensures that the ATC objectives are accomplished. Once a strategy is formulated, a regulation process is evoked provided that the ATCO estimation of the workload associated with the task load does not match the desired workload (Figure 3-10).
For instance, if the air traffic scenario is perceived to be complex and the ATCO is already very busy (high workload), when a flight would request a new cruising FL that is more efficient for its operation, the ATCO would not clear the flight to the requested FL until they can focus on assessing the possibility of climbing/descending the flight. On the other hand, if the ATCO is less busy, even if the situation is perceived to be less complex, they will have enough cognitive resources to elaborate a plan with sufficient anticipation in order to be able to allocate the requested FL to the flight. The degradation of the flight efficiency due to the selection of the strategy can be captured by metrics such as excess flying time, which quantifies the additional time spent by a flight in an airspace sector compared to the optimum profile (Solomos et al., 2005).

![Diagram](image)

**Figure 3-10 Workload and cognitive stages**

As summarised in Figure 3-10, workload is both affected by the task load demand resulting from the strategy selection process (the more difficult the tasks, the higher the workload) (Loft et al., 2007, Sperandio, 1978, Neal et al., 2013) and by the actual performance of the ATCO e.g. an error can cause a subjective feeling of insecurity of the ATCO, leading to higher workload levels (Hilburn, 2004).
In turn, the workload affects the perceived complexity or in other words, the higher the workload, the more complex the air traffic scenario perceived by the ATCO (Hart and Staveland, 1988).

The selection of the strategy depends on the ATCO judgment of the air traffic scenario (the mental picture stored in the working memory), which in turn is influenced both by objective air traffic scenario factors and by the individual differences of the ATCOs as discussed in the previous section. (Hollnagel, 2002) divides the types of strategies or control modes into four groups:

- **Strategic**: which is the ideal case, in which the ATCO has large time horizons to optimise the operations.
- **Tactical**: in which strategic decisions are limited to a certain time horizon and the strategies chosen tend to be more rigid, easing the tasks although becoming less efficient.
- **Opportunistic**: anticipation is almost non-existent and tasks are based on the result of the previous task. No strategic plan is achieved.
- **Scrambled**: typical of “zero control” situations in which the operator is no longer in knowledge of what is being done.

The selection of the control mode indicates the perception of the complexity by the ATCO given the air traffic situation and their instantaneous workload state (Tobaruela et al., 2014b). (Hollnagel, 2002) develops a qualitative relationship between time pressure which is an indicator of workload (less available time indicates higher workload levels) and traffic predictability to identify the control mode being used. Similarly to the (Hollnagel, 2002) model, Figure 3-11 reflects the relationship between the control mode chosen and the workload and time horizon for which the traffic is being planned. In this figure the scrambled mode has been removed as it does not reflect any real behaviour of ATCO operations.
Figure 3-11 Qualitative relationship between the control mode chosen and the workload and traffic planning anticipation

When the desired workload corresponds to the ATCOs workload estimation based on the selected strategy and its associated task load, the final process is triggered i.e. action execution.

### 3.4.2.3 Action execution

Finally, the selected strategy formed of a sequence of actions is executed. The actions can be observable (physical manipulation of ATC systems or verbal communication) or non-observable i.e. cognitive oriented.

Even though extensive research has been carried out in identifying the observable tasks performed by the ATCOs (Mills et al., 2002, Rodgers and Dreschsler, 1993, Phillips and Melville, 1988, FAA, 2010), the task taxonomies depend on the working practices of each ATC centre and are only transferable at a very high level. The physical tasks include actions such as radio communications, flight data management, ATCO communications or system inputs (Section 2.3.6.1).

### 3.5 ASM and ATFCM Functions Performance: Predictability Limitations

Another capacity factor group identified in Section 3.2 is the performance of the ASM/ATFCM functions. The ASM/ATFCM functions are crucial in preventing ATC from
over-loads (Section 2.3). If air traffic demand is underestimated due to inaccurate predictions, the ATC function will ultimately have to handle the excess of demand, potentially leading to a detriment of safety. If underestimations occur too frequently, the capacity of the airspace will be reduced to ensure that excess of demand can be safely accommodated (CHAPTER 7).

Predictability is fundamental to achieve high detection accuracy, thus proposing effective ASM/ATFCM resolution measures with sufficient anticipation. When these functions lack sufficient predictability, they become reactive and cannot strategically optimise their performance. A degraded performance of the ASM/ATFCM functions can have negative effects on airspace capacity, fundamentally through the creation of safety buffers that reduce airspace capacity in order to account for unexpected air traffic demand.

On the other hand, when predictability inaccuracy leads to air traffic demand underestimations, no effect will be found on the airspace capacity although the cost-efficiency of the ACC performance will be reduced due to underuse of the airspace volume (CHAPTER 5).

3.6 Cost-efficiency Limitations

In Section 2.3.3 it was identified that the more operational sectors open, the higher the capacity delivered in the ACC. This finding implies that airspace capacity can be achieved solely through an increase in the number of operational sectors open, regardless of the performance of the rest of airspace capacity factors.

Nevertheless, if capacity aims to be enhanced solely as a function of the number of operational sectors open, this incurs a negative effect on the cost-efficiency of ATC centres. ATCOs are expensive resource, whose use has to be determined in line with the expected air traffic demand that the ATC centre expects to handle.

In the current economic environment, since the economic crisis of 2009, cost-efficiency is perceived as one of the key KPAs for ATM performance in Europe, if not the most important. Therefore, airspace capacity cannot be assessed without accounting for this factor, as recognised by the interviewed SMEs.
Cost-efficiency, understood as the amount of resources (ATCOs) used, is fundamentally driven by the performance of the long-term planning process (Section 2.3.4), which subsequently relies on the predictions made at the different stages of the process.

The long-term planning function expands from long-term to strategic time-frames. During the long-term time-frame predictions are based on economic indicators and long-term traffic growth estimations (e.g. (EUROCONTROL, 2010)). An inaccurate estimation of long-term ACC requirements can lead to stationary inability to cope with future air traffic demand.

During the strategic time-frame, an incorrect prediction of the air traffic scenario on the day of operation can yield imbalances between required and available workforce for a specific airspace configuration. Factors to be predicted include air traffic demand and traffic flows, military activity (airspace availability) and weather forecast. Even though the maximum capacity of each operational sector remains constant, if a sector cannot be opened due to insufficient workforce, the available capacity is effectively being reduced.

3.7 Automation Workload

As discussed in Section 2.1, automation is gradually being introduced into the ATM system, with machines performing tasks previously accomplished by a human operator and new automated systems developing new tasks. In capacity terms, the objective is to free the human operators’ mind to enable them to accomplish additional tasks, thus increasing capacity (Metzger and Parasuraman, 2005, Willems, 2004).

Research shows that automation can potentially free human mental capacity, hence reducing the human workload and support the execution of human tasks with more accurate information (Gray, 1966, Kopardekar et al., 2008a, Prevot et al., 2008). However, (Wiener, 1988) states that, through the introduction of automated tools, workload is not reduced but merely shifted towards other system components. Therefore, if the information to be processed by the automated system exceeds the machine capabilities, these systems can become saturated.

In addition, automated systems must ensure certain standards especially in terms of reliability and robustness. This implies that ATCO workload could not simply be decreased through
automation workload at the expense of reduced ATC safety (Yousefi and Xie, 2011). The reliability of the ATC system has to be ensured not only at the machine level but at the level of the human-machine integrated system. (Lisanne, 1983) provides a description of scenarios in which the introduction of automation into the ATC room increases the probability of issues related to system recovery and the ATCO performance when there is a need to take over the role previously performed by equipment.

The maximum automation workload is dictated by the information processing capabilities of the automated system such as memory storage, computing power, bandwidth and quality of input data. Even though the memory capacities are foreseen to become the bottleneck of future processing systems (Burger et al., 1996) the enormous development of processing capabilities supports the assumption of considering the automated systems as systems with unlimited capacity. Therefore, this thesis does not include this factor group in the development of the capacity estimation framework.

3.8 Other Factors

There are other factors that can indirectly constrain airspace capacity. In terms of developments and innovation, the ATM system is characterised by its resistance to evolution compared with other components of the air transport system such as aircraft technology, e.g. engines. The ATM system is safety-critical, characterised by a great conservatism, in which changes are slowly implemented over large time-frames. For instance, within the current European ATM modernisation initiative SESAR, the implementation of the developed technologies and concepts is predicted to be spread over a 30-year period.

The large lag between the development and the final implementation and operational use of a technology or concept is due to a group of factors, referred to as the implementation factors. Such implementation factors can be divided into four groups: procedural inertia, cost/benefit assessment, regulatory factors and technology availability.

The procedural inertia group embeds all the factors, forcing the ATM system to operate as it used to operate in the past as opposed to embedding and harmonising the implementation of new technologies and concepts. Procedural inertia factors include acceptance, motivation,
adaptation and trust in the new implementation. In fact, human operators do not always use new technologies and concepts in the way they were designed, due to the appearance of one of these factors (van de Merwe et al., 2012), hence the new implementations are not used to their full potential.

A novel technology or concept can be prevented from being implemented due to cost-benefit imbalances. The multiple stakeholders involved in the ATM system (Section 0) on top of the national fragmentation, especially in European airspace, can lead to scenarios where the new deployments are not supported by all the relevant actors, who may have different agendas. In this respect, one of the main objectives of the ATM modernisation initiatives has been to overcome fragmentations by proposing harmonising solutions (Section 2.5).

Regulatory factors include safety assessment and certification factors and economic and political factors. The former are the main drivers in the evolution of the ATM system since safety has to be ensured throughout. The latter account for any external factor to the air transport operation dictated by national authorities that can indirectly affect the development of the ATM system. For instance, in the current economic environment in Europe, policies related to cutting costs have reduced the potential of development programs within the SESAR modernisation initiative, thus slowing down the program development.

### 3.9 Summary

This chapter has developed a definition of en-route airspace capacity, stressing the characteristic features of it. It has subsequently identified the main airspace capacity drivers. This has been accomplished through a review of existing literature, a review of UK’s CAA sector overload reports and interviews with SMEs.

This methodology has unveiled six major capacity factors groups:

1. Spatio-geometrical factors contributing to the so-called theoretical capacity;
2. ATCO workload factors, driven by the individual cognition of ATCO and its perception of objective complexity factors;
3. ASM/ATFCM functions performance factors, driven by the ability to predict air traffic demand (predictability);
4. Cost-efficiency factors that account for the cost of increasing capacity through an intensive use of ATCOs;
5. Automation workload factors which are fundamentally driven by the processing capabilities of the automated systems; and
6. Other factors, which include the drivers for the successful implementation of novel technologies and concepts in the ATM system.

Only factors 2, 3 and 4 are considered relevant within the scope if this thesis for the reasons summarised below.

As a result of the interviews with SMEs, spatio-geometrical constraints have been envisaged to be the main capacity bottleneck in a long-term fully automated environment. However, until that state is reached, the current ATM system has been found to be operating significantly below its theoretical capacity. This has been demonstrated for the MUAC airspace, confirming the findings of previous research.

ATCO workload has been found to be a fundamental capacity driver, which can be enhanced through increased predictability and automation support.

SMEs and sector overload reports have revealed the increasing importance of the ASM and ATFCM functions in ensuring that ATCO workload is maintained within safety limits and have suggested that they could potentially constitute a bottleneck itself due to their increasing importance.

Furthermore, SMEs have identified that capacity can be achieved at the expense of low cost-efficiency levels in the ACCs. However, this is not a realistic assumption in the European environment after the economic recession of 2009. Therefore, there as need to capture the effects of cost-efficiency on airspace capacity.

Automation workload and other factors have been excluded from further analysis in this thesis. Regarding the former, it is assumed that computer processing capabilities of the ATM systems are unlimited. The justification for this assumption relies on the fact that automation processing capabilities have not been identified in past literature as a capacity bottleneck themselves. Besides, the modelling of such a factor would require an in-depth
characterisation of computer machines, which lies out of the scope of the thesis, which focuses on operational aspects of ATM.

Regarding the latter, the other factors identified in this chapter fundamentally rely on behavioural, political and regional drivers beyond the scope of the thesis.

The identification of the most relevant airspace capacity factors in this chapter has provided the basis for the analysis of capacity estimation methodologies and their ability to accurately quantify airspace capacity. This assessment task is developed in the next chapter.
CHAPTER 4 REVIEW OF CURRENT AIRSPACE CAPACITY ESTIMATION METHODS

The capability to accurately estimate airspace capacity is crucial to support an efficient ATM system (Section 4.1). The current chapter reviews existing capacity estimation techniques through a literature review and discussions with SMEs from principal ACCs in Europe in order to assess their strengths and weaknesses.

Two main categories are found in this review: capacity estimation methods based on workload modelling (Section 4.2) and those that do not fall into the previous category (Section 4.3). Each method in the first group is discussed both in terms of the simulation technique used to replicate air traffic scenarios and the model used to estimate human performance.

The limitations of existing techniques are discussed in Section 4.4 based on the findings on airspace capacity factor tasks in CHAPTER 3. Section 4.5 proposes a novel capacity estimation framework to overcome the shortages of existing capacity estimation techniques, capturing the key drivers identified in CHAPTER 3.

4.1 The Importance of Airspace Capacity Estimation

It is widely recognized that airspace capacity estimation is a crucial task in optimising the ATM system (Krozel et al., 2007). The main objective of airspace capacity estimation is to identify the maximum air traffic demand that ATC can safely control. These estimations are especially important for the ASM/ATFCM functions, which protect the ATC function from over-deliveries, thereby ensuring a safe traffic flow (Section 2.3.2). Predictions of air traffic demand in excess of the airspace capacity thresholds identified through the airspace capacity estimation process, trigger ASM/ATFCM actions (Welch et al., 2007).

An accurate airspace capacity estimation is therefore key to an efficient use of the airspace, avoiding underuse as well as ensuring that safety is not being comprised due to any excess in air traffic demand.
Airspace capacity estimation has been identified as a fundamental task to support airspace modernisation (Majumdar et al., 2002). As such, airspace capacity estimations are developed over strategic time-frames of the ATM system, to support the optimal introduction of new systems, operations and procedures. Given the major changes proposed by SESAR, with the implementation of TBOs (Section 2.5.1), airspace capacity estimation is expected to be a major challenge for the future.

There are numerous capacity estimation techniques currently in use, which essentially model the factors affecting airspace capacity. Two main categories can be distinguished: those focussed on modelling ATCO workload and others, which aim to model factors beyond ATCO workload. The next section reviews these groups and discusses their strengths and weaknesses in reliably estimating airspace capacity.

4.2 Methods Focused on Workload Modelling

Airspace capacity has traditionally been identified as the maximum air traffic demand generating acceptable ATCO workload levels (Section 3.1) (Majumdar et al., 2002). It highlights the key link between ATCO workload and ATC safety. (Rodgers et al., 1998) for example shows the direct relationship between ATCO operational errors (safety degradation) and higher workload levels (Section 3.4).

The workload or in other words, the effort created to accomplish the task load (Section 3.4), is not directly observable i.e. it is a construct, and has to be inferred from the measurement of other observable magnitudes (Pawlak et al., 1996, Majumdar et al., 2002, Tobaruela et al., 2014b). Thus, workload modelling is necessary to estimate workload.

As a first step, this requires the replication of representative air traffic scenarios. Three main approaches have been used (NLR, 2002b, Davis, 1971, EUROCONTROL, 2007):

- Fast Time Simulations.
- Real Time Simulations (RTS) or Human-In-The-Loop (HITL) simulations.
- Replication without simulation.

The outputs from the scenario replication techniques are used as inputs to evaluate ATCO
workload using different models:

- Analytical methods: these estimate workload and capacity using functional relationships of air traffic characteristic factors, or in other words the complexity factors.

- Human factors methods: these model and measure human performance under different traffic demand scenarios. Within this group, two sub-categories can be found:
  - Human performance simulation, which consists in modelling human factors through FTS.
  - Human performance measurement, which consist in actual measurement of ATCO workload (and other human factors metrics) directly from the ATCO in RTS.

- SMEs assessments: these methods are based on expert ratings of airspace capacity based on their experience and knowledge of the system.

In summary, the workload modelling techniques can be classified in terms of how the scenarios for the capacity assessment are being simulated (the simulation type) and which model for the workload estimation is being used. Figure 4-1 shows the different possibilities for ATCO workload estimation as a function of the simulation technique and the workload modelling method.
The next sections detail each of the simulation techniques and their associated ATCO models as in Figure 4-1.

4.2.1 Fast Time Simulation (FTS)

A FTS reproduces the operations of the ATM system in accelerated time i.e. the sequence of events happens faster than in real life (Davis, 1971). FTS tools can be classified depending on the level of detail. (Odoni et al., 1997) differentiate between three categories: macroscopic, mesoscopic and microscopic. These categories range from low to high detail respectively. In an airspace capacity estimation context, FTS tools are included within the microscopic or mesoscopic level of detail. This level of detail is required to enable a correct modelling of the interaction between aircraft performance and the ATCO actions that drive their workload.

FTS tools can also be classified in terms of their spatial coverage (Odoni et al., 1997). Even though the focus in this thesis is on en-route operations and associated FTS tools, other tools
exist for ground or TMA operations. Recently, FTS tools are aiming at integrating all coverage areas of the ATM system, i.e. *gate-to-gate* FTS tools.

This section focuses on FTS tools that are currently in use by both industry and research communities. These tools are identified through literature review and discussions with SMEs from the main ACCs in Europe (Eurocontrol, UK, Spain, Italy, Switzerland and Germany). The two main modules (traffic generator and workload estimation as previously discussed) are described below.

**4.2.1.1 Traffic generation**

The traffic generator creates a simulated air traffic demand through a given airspace during a limited period of time. The traffic sample can be extracted from a real traffic scenario or generated tailored to the analysis needs. Characteristics of the traffic (e.g. level of demand, type of aircraft and performance, and navigation equipment) and the airspace (e.g. procedures, military areas, sector geometry, ATC capabilities, routes and navigation aids and weather) are selected pre-simulation as they affect the air traffic performance.

Aircraft performance in ATM FTS tools is modelled using point-mass aircraft kinematics with the use of aircraft performance databases such as Base of Aircraft Data (BADA) developed and maintained by Eurocontrol. Although, the modelling inaccuracies introduced by this approach have been well investigated, many unknowns still remain (Suchkov et al., 2003), and these inaccuracies should primarily be diminished with the more accurate databases flight performance models.

**4.2.1.2 Human performance modelling**

FTS tools simulate the air traffic and the human performance associated with the control of such traffic. The performance of the ATCO is evaluated through models, fundamentally focused on estimating the ATCO workload as the main human performance indicator (Section 3.4). This is achieved through logical mechanisms that replicate the human decision-making process and the cognitive processes that enable these processes. The development and calibration of these logical mechanisms is achieved pre-simulation and depends on the specific working methods of each ACC.
Logical rules are triggered during the simulation when air traffic events occur. This is the reason why these types of simulators are usually referred to as discrete-event simulators. The conditions required for triggering events differ between each specific FTS tool and even within the same tool, events can be included or excluded depending on the specific needs of the analyst. Examples of air traffic events include amongst others (Software, 2011):

- Entry to an airspace sector
- Exit from an airspace sector
- Predicted loss of separation minima between two flights
- Crossing of significant trajectory points (Top Of Descent (TOD) or Top Of Climb (TOC)).

When events occur during the simulation, the FTS tool evaluates the conditions of the air traffic and airspace and assesses which of the pre-defined logical rules for human performance modelling meet the triggering conditions.

The rules triggered by the simulation events reproduce the actions that the ATCO would carry out in a real environment. A unique set of air traffic and airspace conditions is uniquely associated with a unique rule. Therefore, with this approach the ambiguities between ATCOs cannot be modelled (Davis, 1971).

Numerous models have been developed to explain the ATCO functions and their decision-making process. These models can be clustered into two main groups: open-loop and closed-loop models (Loft et al., 2007).

**Open-loop models**

The open-loop models evaluate workload as a function of task demands, which are in turn generated by source factors such as the complexity of the traffic situation and the airspace characteristics. These models create functional relationships between objective traffic characteristics of the air traffic scenario (e.g. traffic count) and workload.

This modelling approach is based on the assumption that workload is solely a function of tasks demands and these are generated by the air traffic scenario. These workload modelling
architectures have been extensively used due to the simplicity of the concept as opposed to open-loop architectures (Cho et al., 2011, Leiden et al., 2003, Majumdar and Polak, 2001, Lee and Prevot, 2012) (Mogford et al., 1995).

Within the closed-loop models, there are two fundamental means in calculating the effects of the events on ATCO workload: task-time methods (e.g. (NLR/EEC/AENA, 2003)) and human cognition modelling methods (e.g. (Loft et al., 2007)). The following paragraphs discuss both methods.

Task-time methods

Human performance modelling through task-time methods is a widely extended technique not only in ATC but in other fields such as military human performance e.g. (Dahn and Laughery, 1997). The basic principle of these methods is that air traffic events trigger tasks to be performed by ATCOs. The task load is related to workload in terms of the relative difficulty of accomplishing the task and its duration. [4-1] mathematically expresses this relationship, where “i” represents each of the modelled tasks:

\[ \text{Task load} = \sum_{i} (\text{weight x duration})_i \]  

[4-1]

The definition of the modelled tasks depends on the working methods of each ACC and have to be identified through task-analysis methods e.g. (Kallus et al., 1999). Additionally, each of the modelled tasks need to be associated with a level of difficulty and a time-duration for task completion. This is achieved through observations during ATC operations and SME rankings (ATCOs) (Ratner et al., 1972) or by SME calibration if the analysis involves the assessment of a non-implemented procedure or technology e.g. free-route environment (Leiden et al., 2007).

In Europe, task-time methods are very widely used in the industry (ACCs) with an emerging dominance of AirTOp and a gradual decline of Total Airspace and Airport Modeller (TAAM) (Table 4-1). In the US task-time methods are rarely used in the industry (e.g. (Board, 2010) to estimate ATCO workforce demand.
Table 4-1 Use of FTS tools of interviewed countries

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The next paragraphs outline the fundamentals of the most common FTS tools using task-time methods.

- **Total Airspace and Airport Modeller (TAAM)**

TAAM was the most popular FTS tool in the late 1990’s and early 2000’s, primarily focused on airports, which were the primary capacity bottlenecks during that period. Apart from the German ANSP (DFS), TAAM was never considered reliable for en-route ATM simulations due to the simplicity of the logical rules used to reproduce ATCO performance and due to the simplicity of the workload calculation (functional relationship accounting for aircraft count, number of conflicts, level changes and coordinations (Majumdar et al., 2005)).

Most of the interviewed ANSPs stated that although they have old versions of TAAM they no longer pay licenses for software maintenance, therefore this FTS tool is likely to completely disappear in the near future.

- **Reorganized ATC Mathematical Simulator (RAMS)**

The Reorganized ATC Mathematical Simulator (RAMS) was originally created as an en-route airspace simulator and has evolved over the years to a gate-to-gate (including ground and airspace operations) simulator. RAMS represents an enhancement over TAAM in the human performance modelling module, although the traffic generation is considered to be less accurate (Sillard et al., 2000). TAAM and RAMS can therefore be seen as complimentary FTS tools. For instance, (NLR/EEC/AENA, 2003) uses TAAM to evaluate
traffic performance on arrival (more accurate air traffic modelling) followed by a RAMS simulation to estimate workload.

The main drawback of RAMS is the modelling of the ASM/ATFCM functions. In RAMS, these functions are not actually simulated. Instead, their performance is defined before simulation. This approach is not realistic, as it does not capture the relationships between the ASM/ATFCM functions and ATC. For instance, a definition of the timeline for the airspace sector configuration (ASM function performance) is defined before the simulation. The airspace configuration will follow this schedule regardless of the necessities of the ATC function during the simulation, which can significantly differ from those pre-defined.

RAMS tool has been frequently used in the research domain to assess the impact of improvements on ATCO workload. For instance, (Ochieng and Polak, 2003) assessed the impact of RVSM, Airborne Separation ASsurance (ASAS) or free-flight routes and (LINK2000+, 1999, Bonnier, 2004) the effects of the introduction of data-link.

- *AirTOp*

Over the last few years AirTOp has arisen as the main alternative to RAMS. Its better interface and modular design enables easy implementation of functional add-ons to the simulation e.g. an Arrival MANager (AMAN) or specific airspace users business models.

In addition, AirTOp has been adopted by Eurocontrol as the principal FTS tool for its support for evaluating new SESAR-related concepts e.g. business trajectory, ATFCM dynamic Demand & Capacity Balancing (dDCB), free routing and Collaborative Decision Making (CDM).

Human modelling in AirTOp uses the same approach as RAMS, a task-time model of ATCO workload based on triggering pre-specified rules by airspace events. The main enhancement of AirTOp over RAMS is the dynamic simulation of ATM functions other than ATC, i.e. the ASM/ATFCM functions. In AirTOp, the performance of these functions is included in the simulation, allowing to assess the relationship between ASM/ATFCM and ATC.

*Human cognition modelling*
In order to account for the complex mental processes of the ATCO, other category of FTS human performance modelling focuses on the cognitive processes.

Similarly to the task-time methods, cognitive processes have to be identified and captured by the FTS tool to compute ATCO workload e.g. (Dittmann et al., 2000). In the ATC domain, cognitive architectures integrated in FTS tools have traditionally been based on Wickens’s Multiple Resources Theory (MRT) (Wickens, 2002). This cognitive architecture is based on the findings on the effects of task interference on human performance (Wickens and Yeh, 1983).

Depending on the demand of cognitive resources created by a set of tasks and the interference between them, the performance of accomplishing such tasks may vary. Four cognitive channels are identified within this theory (spatial, verbal, auditory and visual). When the tasks compete for resources within the same cognitive channels, the efficiency of accomplishing the task is lower than when there is no multi-tasking or resources competition.

The paragraphs below review the most currently used cognitive architectures for modelling human performance.

- **Micro Saint Sharp**

Micro Saint Sharp is a commercial software platform developed to evaluate complex human-machine systems (e.g. fighter pilots job). Observable and non-observable tasks are modelled in Micro Saint Sharp as a task network. This approach is significantly more detailed and complex than the logical rules created with the task-time FTS tools\(^2\).

Micro Saint Sharp is used in (Leiden et al., 2007) to compute workload in different automated scenarios with a functional relationship similar to [4-1] but with a human performance model based on cognitive channels, similar to Wickens’ MRT.

- **Man Machine Integrated Design and Analysis System**

\(^2\) Personal communication with Allion Science and Technology Corporation commercial department
The focus of the Man-machine Integrated Design and Analysis System (MIDAS) is also on the human-machine system, although it is not only restricted to the ATM domain. MIDAS embeds a cognitive, perceptual and motor model of the human and a detailed model of the machine system, able to simulate the relationship between them.

Workload is subsequently computed based on the tasks and resources required by the visual, cognitive and physical actions (Sebok et al., 2012). The MIDAS FTS tool has been used as a high fidelity human performance simulator in large scale ATC simulations (Gingell et al., 2005).

- **PUMA-MWM**

The PUMA-MWM is the most extensively used cognitive FTS tool in ATC worldwide. Modelling the ATCO actions in PUMA involves defining a cognitive architecture for the ATCO mental processes. This is implemented through Wickens’s MRT. The calibration of this cognitive architecture is a complex process that involves multiple iterations with experts’ (ATCOs’) insights. PUMA models the decision-making processes of ATCOs when air traffic events occur. This has led to simulation platforms in which the air traffic events are introduced by another FTS tool, such as in AENA’s implementation approach.

In this approach RAMS is used as the traffic and events generator. MWM is instead only used as a FTS for human performance modelling (Boogaard, 2007). In addition, after simulation workloads are computed and sector capacities identified, these local sector capacities are used in turn by another simulation in order to evaluate the network performance with these new capacities (Figure 4-2).
This simulation architecture has been used for SESAR validation activities with a tailored calibration of the cognitive processes. In addition, this architecture has been attempted to be used in real-time for workload prediction for 3 hours anticipation until execution (Ham et al., 2011). Real trajectories are used as inputs to the RAMS simulator, which generates continuously events that are processed by MWM to give workload predictions approximately every 20 minutes.

**Closed-loop models**

On the other hand, closed-loop models (Hart and Staveland, 1988, Sperandio, 1978) understand workload as the result of an iteration process, during which, given a specific traffic scenario, a strategy is chosen to achieve certain performance standards. The selection of the strategy yields different task loads or tasks to be accomplished. In these models, workload is not a function of the objective traffic characteristics only, but more importantly, a function of the strategy chosen. This strategy is a function of each individual ATCO, who will select a control strategy depending on individual and objective air traffic factors.

Capturing the individual differences is a significant and probably unachievable effort. No model has been found in the literature accounting for individual differences between ATCOs. Besides, the capture of these factors would raise social issues, such as the legitimacy to effectively show that some ATCOs are more skilful than others. As found during the
interviews held with MUAC SMEs (CHAPTER 8), this could be a potential unrest factor within an ACC.

Workload is finally computed as a result of the amount of tasks and associated complexities triggered by the air traffic events and mediated by the human performance model. The computed workload derived from the simulation is used to estimate the maximum capacity of the airspace.

4.2.1.3 Capacity estimation for Fast Time Simulation methods

The traditional and more extended way of calculating airspace capacity is based on FTS task-time methods as the one outlined in (Flynn et al., 2003, NLR/EEC/AENA, 2003). In this approach, an iteration of traffic scenarios simulations is prepared, which covers the vast majority of traffic combinations that can be encountered in the airspace, or at least those scenarios causing capacity concerns. For instance, simulations may be prepared capturing departure-type scenarios, arrival-type scenarios and a mix of both.

After the simulation of the scenarios a scattered plot for traffic and workload is created in which the general trend of workload as a function of traffic can be observed. These set of scatter points are fitted to a curve that represents the mathematical relationship between both magnitudes for the airspace being simulated.

Finally, the capacity of the airspace corresponds to the maximum workload in the functional relationship just calculated. The definition of the maximum workload level is not clear though and traditionally this has been defined as a percentage of time being busy doing non-monitoring tasks. Most studies have set the maximum workload threshold as the ATCO being occupied 70% of the time (Majumdar, 2003).

4.2.2 Real Time Simulation (RTS)

In RTS a reproduction of ATC operations occur with a complete relation of the time sequence of events of real life, thus ATC actors such as ATCOs can participate in the simulation (Davis, 1971). This is the reason why this technique is also known as HITL simulation. Depending on the fidelity levels of the RTS in replication air traffic scenarios and
the ATCO working environment, different low fidelity RTS can be identified. An example of such low-fidelity implementations is gamings in which SMEs simulate future concepts in a low fidelity simulation, although the aim pursued is usually the clarification of new concepts rather than the estimation of capacity (Rafidison, 2010). This low-fidelity RTS approach is therefore excluded from the discussions of this section.

RTS are more representative of actual ATC operations than FTS since they take into consideration the actual performance of real actors (ATCOs) in a mock-up environment. RTS are therefore usually conducted as a validation exercise in the last phases of the introduction of new concepts (Revuelta, 2004).

RTSs are not only conducted for the estimation of capacity or the evaluation of new concepts, but also for training. In fact, the initial training of ATCO-trainees is accomplished through RTS and refreshment trainings of qualified ATCOs uses as well RTS as a means to maintain performance standards.

In order to estimate airspace capacity from RTS it is necessary to use a concrete method for workload measurement. (Farmer and Brownson, 2003) make a revision of the available methodologies which fall into one of the following three categories: performance-based measurements, subjective estimations, and physiological measures. Many other techniques exist for workload measurements in domains other than ATC (Chin et al., 2004), however the focus in this thesis is on ATC-related workload measurement techniques.

Airspace capacity with this method is determined by increasing the air traffic demand and complexity until the ATCO shows signs of saturation (Kopardekar et al., 2008b).

4.2.2.1 Performance-based measurements

In this category, workload is estimated based on the performance of certain tasks which the ATCO is required to fulfil. The tasks being assessed can be directly related to the ATCO job (primary-task analysis) or not related to the ATCO job (secondary-task analysis) i.e. artificially created (e.g. mental arithmetic) (Kaber et al., 2007). The primary-task analysis provides accurate estimations of the performance of the ATCO in accomplishing its objectives, and especially of the task of interest, whilst the secondary-task represents the
amount of spare ATCO capacity i.e. the spare amount of ATCO resources.

Whilst it is apparent that the performance of primary tasks is directly linked to workload, the rationale for secondary tasks is that their performance will degrade as workload increases and less ATCO resources can be employed to achieve the secondary tasks.

This is a very intrusive method as it interferes in the normal tasks and is very dependent on the individual strategies and working methods of each ATCO.

### 4.2.2.2 Subjective estimations

Subjective workload estimations are reported ratings from the ATCO. Even though these are generally self-reported, they can be determined by external ATCOs (e.g. over-the-shoulder (Manning, 2000)).

Subjective workload estimation can be carried out during the simulation or post-simulation. The former is usually achieved through appropriate systems to which workload ratings can easily be input and recorded while the latter is typically achieved through interviews and questionnaires.

This technique is especially important for the development of new systems, in which the ATCO, who will ultimately be the operator of the system, is included in its preliminary design and development. This builds up their trust in the new system, a fundamental implementation factor for correct development of ATC systems (Section 3.8).

The paragraphs below describe the most common performance-based measurements implementations.

- **Air Traffic Workload Input Technique (ATWIT) and Instantaneous Self-Assessment (ISA)**

The ATWIT (Stein, 1985) and the ISA techniques (Tattersall and Foord, 1996) are conceptually the same subjective workload measurement technique. The basic procedure is that the ATCO rates workload, according to a given workload scale, periodically during the simulation or during operations. The ATWIT technique has for example been used in various
US studies assessing the nature of future ATCO/automation interactions (Prevot et al., 2012).

ISA typically uses a 5-point scale (1=under-utilised, 2=relaxed, 3=comfortable, 4=high, 5=excessive) although this can be modified and more levels can be included. For instance, (Prevot et al., 2008) estimates workload on a 1-7 scale in order to evaluate the feasibility of implementing automated separation assurance concepts in a TBO environment.

The ISA technique is one of the most extended techniques used at ACC level (e.g. MUAC) and also in the research community when RTS are being carried out (e.g. (Whitaker and Marsh, 1997)).

- **Subjective Workload Assessment Technique (SWAT)**

The SWAT technique is similar to the ISA technique. SWAT has three dimensions that represent workload: time load, mental effort load and stress load. Each of the dimensions is rated on a 3-points scale, thus obtaining a final workload range of 27 points.

This multidimensional workload scale is however more demanding when used during the simulation and can lead to higher ATCO interference.

- **NASA Task-Load Index (TLX)**

The NASA TLX is a post-simulation or post-operations subjective workload assessment technique based on subjective ratings of task-related (task difficulty, time pressure and activity type), behaviour-related (physical effort, mental effort and individual performance) and subject-related (frustration, stress and fatigue) scales (Hart and Staveland, 1988).

Workload is calculated using a weighted analytical formula. ATCOs are asked prior to the simulation to rate the relative importance of all of the workload factors. Following the simulation, they are asked again to rate, on a 20-point scale, the importance of each factor during the simulation exercise. The workload computation is the result of the sum of the post-simulation ratings weighted with the pre-simulation factor ratings.

- **MALvern Capacity Estimate (MACE)**
The MALvern Capacity Estimate (MACE) is a post-simulation subjective process for airspace capacity estimation. It consists of an iterative process in which ATCOs assess if the amount of traffic controlled is above or below capacity.

To this aim, one-hour simulations are conducted after which the ATCOs assess by which percentage traffic should have been reduced or increased in order to match the airspace capacity. The ATCO estimates can be developed both for peak (instantaneous) and sustained capacities.

In this sense, the MACE process is not a workload estimation method per se, but a direct capacity estimation method. However, in reality the ATCO judges the capacity based on their individual perception of the amount of workload required to control the traffic in the one-hour scenarios. Therefore, workload is being indirectly measured.

### 4.2.2.3 Physiological measures

These measurements rely on the assumption that workload variations are manifested in physiological reactions. This fundamentally includes measures of brain and heart rate activity e.g. (Hasan et al., 2010, Kaber et al., 2007), pupil dilation and movements e.g. (Roessingh and Zon, 2004) and skin conductance, e.g. (Nourbakhsh et al., 2012).

These measurements can only be carried out during simulations and not during operations due to the high degree of intrusiveness. The main advantage of these measures is that the physiological indicator shows variance even when there is no physical action. This is the only technique that achieves a measurement of a human non-observable magnitude. This fact makes physiological measures very appropriate in low activity scenarios (NLR, 2002b).

### 4.2.3 Replication without simulation

Capacity estimates through workload modelling can be obtained without simulation. This is the case for analytical modelling and SME assessments. However, both methods differ in the means used to estimate capacity (mathematical formulae and expert ratings respectively). Furthermore, neither replicates traffic scenarios.
4.2.3.1 Analytical modelling

Analytical modelling consists in developing a functional relationship between capacity and its underlying drivers, fundamentally workload drivers [4-2]. As shown in Section 3.4.1, the workload drivers are the so-called complexity factors.

\[ \text{Capacity} = f(\text{complexity factors}) \]  [4-2]

At an ACC level the clearest example of analytical modelling is for US airspace sectors. Sector capacities are calculated using a fixed parameter, the MAP (Section 3.1), which is specific to each airspace sector and a function of the transit time of traffic through the airspace sector (Jaurena, 2009).

Many other research studies exist that have attempted to develop analytical capacity models. For instance (McNally and Gong, 2007) uses aircraft separation as the independent variable in [4-2] and (Dunlay Jr, 1975) evaluates ATCO workload as a function of the specific geometry of each air traffic conflict. (Christien and Benkouar, 2003) use a combination of a macroscopic FTS (AMOC), gathering traffic information (number of flights and interactions between them), and an analytical formula to estimate workload and finally capacity in different types of airspace sectors.

(Chaboud et al., 2000) develop a workload functional relationship based on FTS outputs. The workload formula depends on three variables (number of sector entries, number of flight levels crossed and number of conflicts). The coefficients of these variables are estimated using RAMS workload outputs.

However the most extensively adopted analytical modelling method is the dynamic density approach, fundamentally developed in the US (Laudeman et al., 1998, Kopardekar et al., 2008b, Masalonis et al., 2003).

- Dynamic Density

ATCO workload is the demand caused by the tasks to be accomplished by the ATCO in order to ensure a safe and expeditious flow of traffic (Section 3.4). Even though many factors
contribute to ATCO workload, it is fundamentally driven by the air traffic demand and its characteristics (Mogford et al., 1995). The mathematical representation of the complexity factors of workload is generally referred to as dynamic density (Sridhar et al., 1998). It is used as an ATCO activity indicator. Therefore, it could be included within the human factors models category. However, due to the different approach of dynamic density models in modelling human performance, which are only based on traffic characteristics, it is kept as a separate category in this thesis.

Dynamic density models infer ATCO workload based on functional relationships with air traffic complexity factors (Section 3.4.1). Dynamic density models are developed in a sequential manner:

1. Identification of dynamic density metrics (SME ratings).

The independent variables in the dynamic density function are the dynamic density metrics. These are formed of different variables (e.g. airspace density is formed of aircraft count and airspace volume), which are identifiable directly from traffic i.e. they are not dependent on subjective interpretations.

The selection of the dynamic density metrics is made according to the identification of complexity factors by SMEs (ATCOs). For instance, ATCOs can rate the geometry of air traffic conflicts as a complexity factor, which in turn can be reflected by a dynamic density metric representing the angle between flights in conflict.

By the end of this step, dynamic density can be expressed as.

\[
\text{Dynamic Density} = \sum_{i} \alpha_i x_i
\]  [4-3]

where “\(x_i\)” is each of the dynamic density metrics and “\(\alpha_i\)” the coefficient of the dynamic density metric calculated in step 2.

2. Calculation of the functional relationship parameters through regression.

Once the dynamic density functional relationship has established, the coefficients in [4-3] are
determined using regression. For this regression, workload ratings from ATCOs are needed.

3. Determination of maximum capacity

Finally the dynamic density computation has to be associated to a capacity usage. The relationship between the dynamic density and workload has to be established in order to identify which dynamic density level represents the capacity threshold (Kopardekar et al., 2008b).

4.2.3.2 Subject Matter Expert (SME) assessments

In this category the airspace capacity assessment is solely based on SME ratings, based on their knowledge of the system (Maxwell, 1975). This technique is usually carried out in a structured manner and even with the support of analytical relationships, creating a more structured methodology. SME assessments are usually implemented as the first step in the validation process for the introduction of new system enhancements.

In order to provide more structured approaches to SME assessments, these have been combined with other existing techniques, such as influence modelling.

Influence modelling

Influence modelling is a singular alternative in analytical modelling characterised for an intuitive and easy manipulation (Dawid, 2000). Influence modelling is a probabilistic method used for decision-making in the presence of large uncertainties (Kjærulff and Madsen, 2011). It is based on a mathematical expression of an influence diagram (Shachter, 1986). Influence diagrams are used to evaluate the relationships between different variables in complex systems. The nodes in the influence diagrams are the variables of the system, which are linked. The mathematical expression of the interdependencies is the influence model.

The process for elaborating an influence diagram is as follows (Anthony, 2006):

1. Data gathering to support the SMEs judgments (coming from repositories of validation activities and other assessments).
3. Development of the probabilistic influence model (using again data from any other previous assessments).

The influence modelling methodology has become extended in Europe in recent years. Such is the case in the Episode3 program in which influence modelling is used to assess the overall capacity increases (Graham et al., 2009, Episode3, 2009). Influence models have been used in these studies to establish links between the required performance and the proposed improvements.

However, the analysed influence diagrams during the PhD research were overall developed with limited mathematical strictness, using simplistic linear relationships and lacking a proper validation. Moreover, current SESAR capacity enhancement predictions rely on the results of these methodologies (SESAR, 2008a, Goss-Custard and Shorthose, 1996) (e.g. Figure 4-3). This emphasizes even more the need to develop a capacity estimation framework, the focus of this thesis.

Figure 4-3 Influence diagram (Simonsson, 2011)

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3 Personal communication with Hartmut Koelmann (Eurocontrol, Performance Review Unit)
4.3 Other Methods for Airspace Capacity Estimation

Other alternatives to the most widely extended workload-focused methods have been proposed. (Averty et al., 2003) estimate ATCO workload by evaluating the time-pressure component of workload. The maturing time concept is introduced, indicating the relative time left to perform each of the necessary actions to each flight. This indicator proves to be a good indicator of other physiological measures although the implementation is complex.

Many studies have developed analytical formulae for airspace capacity estimation, e.g. analytical modelling based on FTS (Welch et al., 2007) (Welch et al., 2013, Majumdar et al., 2002). These studies substitute the expert calibration of the dynamic density methods by the FTS outputs and result into similar relationships to [4-3].

Factors other than ATCO workload can also constrain airspace capacity (CHAPTER 3). These are accounted for in (Donohue, 1999) by introducing a capacity degradation matrix. This matrix reduces the ATCO workload capacity by accounting for weather impact and other ground operations factors (e.g. wake vortex separation). However, this study lacks a proper ATCO workload modelling and the results tend to be too general with questionable assumptions: ATCO maximum workload assumed to be able to handle only 15 aircraft per sector regardless of traffic or structural complexity factors.

In general, methods aiming to consider other airspace capacity factors beyond ATCO workload have concentrated in investigating impact of weather and geometrical constraints on airspace capacity. For the en-route domain, studies such as (Klein et al., 2008) show that weather and geometrical limitations are the main capacity bottleneck. (Krozel et al., 2007) make an airspace capacity assessment accounting only for geometrical restrictions and not for workload limitations. The main objective is to evaluate how much a certain airspace volume can be packed with traffic for a given set of traffic flows, air navigation routes and weather conditions (measured by a weather severity index). Weather is modelled as a set of non-navigational volumes of airspace, thus effectively reducing the available airspace volume. Traffic is generated using the Virtual Airspace Modeling and Simulation (VAMS) developed by NASA.
In the simulation, different airspace user weather-avoidance behaviours are modelled and their impacts on the geometrical capacity evaluated. The free flight concept is found to provide the highest airspace utilisation, although this is achieved at the expenses of large airspace complexity. This effect, which is overlooked, could actually restrict capacity before the geometrical bottleneck has been reached.

The geometrical approach can be found more often in other areas than en-route. For instance (Boswell, 1993, Janić and Tošić, 1982) models the capacity of a TMA as a function of the spacing and sequencing characteristic of the arrival flows to an airport and (Barbaresco et al., 2011) determines the minimum spacing between arrival traffic in a runway due to wake-vortex separations.

4.3.1 Integra methodology

The Integra capacity estimation methodology considers that the maximum capacity of the ATC function is reached when any of its components reaches its individual maximum workload (Hudgell and Gingell, 2001). With this approach any actor modelled is assigned a maximum Information Processing Load (IPL) (equivalent to a maximum workload) (Figure 4-4). With this approach all of the airspace capacity bottlenecks identified in CHAPTER 3 can potentially be modelled (except the spatio-geometrical bottleneck).
The Integra methodology embeds a FTS tool that generates events that will be subsequently used to calculate the IPL for each modelled component. The modelling of the components is however very simplistic. For instance, human performance is computed exclusively based on a few events (flight arrival, interaction detection, resolution planning, resolution implementation, monitoring, other trajectory changes and coordination).

Another issue of this methodology is the definition of the maximum IPL for each modelled component, which relies on SME judgments and the task allocation definition between components, which in a complex system such as ATM is difficult to be identified.

4.4 Limitations of Current Capacity Estimation Methods

As discussed in the two previous sections (Section 4.2 and 4.3), current airspace capacity estimation techniques are based on different assumptions associated with each of the models. Given these assumptions, no single of these techniques is found to be able to fulfil all the requirements of airspace capacity estimation (SESAR, 2008d, SESAR, 2008b, Rafidison, 2010).

In fact, airspace capacity estimation techniques are used in a combined manner. Each of them
are typically associated with the specific objectives of each of the stages in the so-called ATM lifecycle (Revuelta, 2004): initial concept development, experimental design and final validation.

Therefore, the different identified techniques have different purposes and are suitable to a certain stage in the ATM lifecycle as captured by the MAEVA process (Figure 4-5). This process, which is followed by the main ANSPs in Europe (Majumdar et al., 2005), recommends the use of the airspace capacity estimation techniques identified in this section in a sequential manner to fulfil the different objectives throughout the ATM lifecycle.

Figure 4-5 MAEVA process with the suggested route map highlighted with blue arrow (Revuelta, 2004)

In this figure, analytic modelling is proposed to be the first technique in the capacity estimation process with the objective of supporting the initial concept development. Analytic modelling may be further enhanced by results coming from subjective assessments. FTS is used in the next stage during the experimental design and previous to the assessment of the proposed concept through RTS. Finally, operational trials precede the final implementation of
the new concept in real operations.

Given the specific purpose of each of the airspace capacity estimation methodologies, as reflected by the MAEVA process, the sections below identify the main limitations of the airspace capacity estimation techniques identified in this chapter. Based on these limitations, a novel airspace capacity estimation framework is developed in Section 4.5

4.4.1 Limitations of Real Time Simulation methodologies

RTS methodologies were shown most representative of actual scenarios due to the actual reproduction of the new system, procedures or operations and due to the involvement of the ATCOs in the simulation. These are the key reasons for using the technique in the late stages of the validation process (Revuelta, 2004). On the other hand, RTS have a reduced flexibility to account for different concepts due to the high cost and time consuming nature of setting up a new RTS.

If the new implementation cannot be accurately represented, then flawed results may be obtained. This is the case for early stages of the design of a new implementation, during which high fidelity RTS might not be necessary as the concept is still lacking the required levels of maturity. In these cases, other techniques (fundamentally SMEs assessments) are typically more appropriate.

Despite being high-fidelity, RTS cannot simulate some aspects of the real ATC environment. This is the case of noise and other environmental factors occurring inside an ATC operations rooms. (Goillau and Kelly, 1996) find that not accounting for these factors may lead to an increase of up to 30% of workload between RTS and real world operations.

In field trials conducted by Eurocontrol for the evaluation of the MTCD tool, it was found that even though the number of tasks required to be accomplished for conflict search and monitoring were reduced with the introduction of the MTCD, the workload increased compared to a scenario without MTCD. This was due to the increase in the cognitive processes associated with the new implementation (Kauppinen et al., 2002). Although this study argues that the increase of workload is due to the non-familiarity of ATCOs with the new MTCD, real operations have shown that MTCD has not been implemented in ACCs due
to the associated workload increase.

Even though workload results are accurate in RTS, as opposed to other techniques in which workload is either simulated or guessed, the selection of the workload measurement method remains as one of the major methodology issues.

Subjective workload measures stand out for their low cost and ease of use, even though self-reporting has been shown to be limited by ATCO bias (memory limitations, self-perception and “want-to-hear”) (NLR, 2002a, Majumdar, 2003). In addition, lack of agreement between the meaning of workload levels for different ATCOs was identified (CHAPTER 9). The main drawback of physiological and performance based measures is their intrusiveness. Their advantage is that they are not affected by the biases of individual ATCOs. These two last measurement techniques were shown to be highly correlated (Buckley et al., 1983).

In addition, due to the cost of conducting RTS, many research investigations have employed operators other than ATCOs to save costs e.g. (Kaber et al., 2007). This raises doubts on the validity of the results when these untrained operators conduct the simulation. Besides, when the simulation experience is very different from current operations, to which the ATCOs are trained, these can suffer from unfamiliarity, which would potentially translate into higher workload levels (Gool and Schröter, 1999).

4.4.2 Limitations of Fast Time Simulation methodologies

FTS methods, compared to RTS, have lower fidelity levels and lower costs along with an increased flexibility. These methods have demonstrated to sufficiently flexible to simulate a wide range of concepts through the re-calibration of the FTS model parameters (e.g. re-calibration of times associated with tasks). These reasons explain the use of the technique in an earlier stage of the capacity estimation process (Revuelta, 2004).

FTS simulation outputs have the risk of producing results that can be hardly “believed”, especially by ATCOs due to the large number of factors and complex interactions happening during the simulation. (Phillips and Marsh, 2000, Kleijnjen, 1995) propose methodologies to validate the results of FTS using a step-wise approach, assessing first the conceptual validity of the model and subsequently the operational validity of the simulation. In this regard,
operational experts, such as ATCOs, are highly recommended to be involved in the simulation process (both for traffic generation and human performance modelling) in order to assess the similarity of the models used in the FTS tools and real operations.

FTS tools have been further split in terms of the human performance model: task-time and human cognition models.

4.4.2.1 Task-time methods

Task-time methods stand out for the simplicity of the human performance model, which is based on a calibration of the airspace events and the human actions triggered. As discussed in Section 3.6, automation effects on ATCO workload are unpredictable and fundamentally driven by cognitive performance. This is an aspect that is hardly captured by task-time methods.

(Loft et al., 2007) develop a detailed comparison of task-time and cognitive approaches, questioning the validity of task-time methods in capturing the relationship between task load and workload, which is highly dependent on the way the ATCO resources are managed. In addition, task demand approaches fail to capture the effects that the introduction of new tools to the ATCO have on the changes of working strategies of the ATCO.

Similarly (Hilburn, 2004) identifies a non-linear relationship between task demand and workload, which raises doubts on the validity of task-time methods. Under increases of task load, ATCOs may decide to change their working strategy and prioritise, therefore a given task may not always be uniquely associated with a given workload level. These findings have recently lead to the use of human cognition models.

4.4.2.2 Human cognition models

Currently existing human cognition models for airspace capacity estimation use Wickens’s MRT approach. This method, which accounts for the effect of cognitive interference, is a first step towards producing more accurate human performance models. Although ATCO workload using cognitive approaches show a non-linear relationship with traffic as opposed to the task-time method linearity, some studies (e.g. (Crutchfield and Rosenberg, 2007)) have
found that with current state-of-the-art FTS cognitive architectures, the relative performance, as opposed to task-time methods, has not significantly increased. Other more accurate cognitive models, such as those in MIDAS, have the main drawback of a very difficult calibration and validation and have therefore rarely been used in the ATC domain.

In addition, ATCO workload depends on the individual ATCO pair controlling each of airspace sectors, for a given set of airspace and operational factors. For instance, the amount of traffic that a trainee can handle is not the same as that by an experienced ATCO, and a demotivated ATCO is potentially going to perform worse than a motivated ATCO.

Ideally, the capacity estimation method should be able to take into consideration these variations. However, currently existing airspace capacity estimation methods, as those reviewed in this chapter, do not account for such individual differences.

4.4.3 Limitations of analytical modelling

Analytical modelling has been demonstrated to be an easy to implement technique compared to RTS and FTS techniques and are therefore used in the first stages of the capacity estimation process (Revuelta, 2004). However, dynamic density metrics have been shown to account only for half of the variance in measured workload, thus are not reliable for airspace capacity estimation (Loft et al., 2007). Moreover, functional relationships for workload are tailored to specific airspaces and working procedures since complexity depends on structural factors and therefore are not transferable between different airspace regions (Sridhar et al., 1998).

4.4.4 Limitations of Subject Matter Expert assessments

SME assessments are the most flexible and quick methods and can be used at any stage of the capacity estimation process. They allow for a large scope analysis, capturing interfaces between different ATM functional areas e.g. capacity and cost-efficiency.

4.4.5 Summary of currently existing methods limitations

Table 4-2 summarises the main characteristics of the four principal capacity estimation
methodologies assessed. The time-frame column refers to the temporal horizon over which
the methodology is ideally applicable as captured by the MAEVA process (Revuelta, 2004).
The output indicates whether the result is qualitative or quantitative. The adaptability
represents the capacity of using the same methodology across different concepts. The
accuracy of the result represents the fidelity of the methodology outputs. The cost and time
indicates both the financial and time costs of setting up, conducting and analysing the results
of the simulation.

Table 4-2 Qualitative comparison of capacity estimation techniques

<table>
<thead>
<tr>
<th>Feature/Technique</th>
<th>Analytical</th>
<th>SME</th>
<th>Fast Time</th>
<th>Real Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timeframe</td>
<td>Concept development</td>
<td>Concept development</td>
<td>Experimental design</td>
<td>Experimental design</td>
</tr>
<tr>
<td>Output</td>
<td>Quantitative</td>
<td>Qualitative</td>
<td>Quantitative</td>
<td>Quantitative</td>
</tr>
<tr>
<td>Adaptability</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Time</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

As it can be seen from Table 4-2 choosing a technique requires making a trade-off depending
on the purpose of the study.

4.5 A Novel Airspace Capacity Estimation Framework

CHAPTER 3 has discussed the main drivers of airspace capacity identifying the importance
of the long-term planning, ASM/ATFCM and ATC functions. The present chapter has listed
the main existing airspace capacity estimation methodologies and discussed their limitations
to model airspace capacity. The main findings from this chapter are summarised below:

1. Airspace capacity estimation techniques are fundamentally focused on ATCO
   workload:
a. The long-term planning function and the subsequent impact of cost-efficiency on airspace capacity was identified as a key capacity driver in CHAPTER 3, however no methodology that captures it has been identified.

b. The ASM/ATFCM functions driven by their ability to predict air traffic were identified as key capacity drivers in CHAPTER 3, however no methodology that captures them has been identified.

2. ATCO workload estimation techniques are not focused on the operational stage and are fundamentally focused on the initial concept development and the experimental design phases of the capacity estimation lifecycle. Although these techniques can be applied to operational trials they present the following main deficiencies (Section 4.4):

   a. FTS are unable to capture individual ATCO strategies and require large post-operations tasks
   
   b. RTS are expensive, interfere with the ATCO during operations and require large post-operations tasks

Based on these limitations a novel capacity estimation framework is proposed in this section. This framework aims to overcome all the mentioned limitations by proposing a 4-step framework as depicted in Figure 4-6.

![Figure 4-6 Airspace capacity estimation framework](image)
Each of the framework steps are described below.

4.5.1 Step 1: Input

The objective of this step is to define the modernisation initiative or initiatives that are going to be assessed with the framework. This step fundamentally includes gathering of information relative to the modernisation step, which may be achieved through:

- Operational and technical specifications;
- Discussions with SMEs; and
- Gathering of historical information from similar modernisation initiatives.

The result of this step is a comprehensive understanding of the modernisation initiative and a thorough compilation of relevant information that can be of use in later stages of the framework.

4.5.2 Step 2: Input evaluation

The objective of this step is to qualitatively assess the main impact of the modernisation initiative relative to the en-route airspace capacity factors identified in CHAPTER 3, based on the knowledge gathered in Step 1. The outcome of this evaluation should be the selection of one of the framework areas in step 3, which are associated to the three en-route capacity factors identified in CHAPTER 3:

- ATCO workload factors;
- ASM/ATFCM functions performance factors; and
- Cost-efficiency factors that account for the cost of increasing capacity through an intensive use of ATCOs.

This framework is therefore limited to modernisation initiatives that have at least one of these three factors as their main impact. For instance, if the modernisation initiative is found to have a main impact on automation workload, the framework would not be applicable.

A more detailed discussion on the implementation of this step is achieved in Section 10.1.
4.5.3 Step 3: Application of framework areas

Once a decision has been made on which framework areas should be used to assess the capacity impact of the modernisation initiative, each of the framework areas are used.

These framework areas are detailed in the next chapters as indicated in Table 4-3. They include the development of methodologies and tools, the application of them to concrete case studies to demonstrate their applicability and the final validation/evaluation to ensure their adequacy in meeting their respective objectives.

Table 4-3 Airspace capacity estimation framework areas and chapters organisation

<table>
<thead>
<tr>
<th>Framework area</th>
<th>Chapter</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost-efficiency area</td>
<td>CHAPTER 5</td>
<td>Development and validation</td>
</tr>
<tr>
<td>Predictability (ASM/ATFCM) area</td>
<td>CHAPTER 6</td>
<td>Development</td>
</tr>
<tr>
<td></td>
<td>CHAPTER 7</td>
<td>Evaluation and application</td>
</tr>
<tr>
<td>Workload area</td>
<td>CHAPTER 8</td>
<td>Development</td>
</tr>
<tr>
<td></td>
<td>CHAPTER 9</td>
<td>Validation and application</td>
</tr>
</tbody>
</table>

The ATCO workload estimation methodology developed in CHAPTER 8, as part of the workload framework area, is focused on measuring ATCO workload from RTS, operational trials or real operations, in order to cover the missing gap encountered in the assessment of current existing workload estimation methodologies. If the capacity estimation of a modernisation initiative is in another stage of the lifecycle (e.g. initial concept design), the methodology applied in this thesis is not applicable and an existing workload estimation technique should be chosen, potentially from the ones reviewed in Section 4.2.

4.5.4 Step 4: Analysis of capacity impact

Depending on which en-route airspace capacity factor the modernisation initiative has an impact, the effect on en-route airspace capacity is differently modelled and depends upon the results obtained from the application of the framework areas. This Step discusses this question.

As seen in CHAPTER 3 en-route airspace capacity is upper bounded by the spatio-
geometrical restrictions of airspace and aircraft i.e. the *theoretical capacity* (Figure 4-6). However, in reality this geometrical capacity is much larger than the capacity that ACC offer to the airspace users: the *available capacity* (Figure 4-6).

The airspace capacity resulting from imposing the restrictions created by the ATC function, fundamentally ATCO workload, to the theoretical capacity is referred to as the *sector capacity* (Figure 4-6). The workload framework area supports the quantification of this buffer to estimate the sector capacity.

The sector capacity still does not correspond to the available capacity. In fact, it is constrained by the performance of its two support functions: the ASM and ATFCM functions. These functions in turn, are driven by predictability factors.

The predictability of the ATM system can directly impact the performance of the ASM/ATFCM functions in terms of safety (lack of predictability for anticipating traffic over-deliveries) and in terms of cost-efficiency (lack of predictability to use the optimum airspace configuration).

The predictability buffer created by the ASM/ATFCM functions yields the *declared capacity* (Figure 4-6). This buffer is created to account for the non-predicted air traffic demand excess. The predictability (ASM/ATFCM) framework area supports the quantification of this buffer.

Finally, the available capacity will only be offered if there is enough manpower to man all the operational sectors for the optimum airspace configuration. The ACC centres, like any industry, are driven by the profitability of the operations. In this regard, ACC centres plan their necessary resources (planning function) according to the estimated demand. An over-allocation of ATCOs would generate a cost-inefficient ACC performance, whereas an underestimation of the resources would be translated into capacity shortages.

The reduction created by the cost-efficiency buffer, fundamentally introduced by the long-term planning function, on the declared capacity results in the *available capacity* (Figure 4-6). The cost-efficiency framework area supports the quantification of this buffer.
4.6 Summary

This chapter has discussed the importance of airspace capacity estimation in supporting the development and implementation of future ATM modernisation initiatives and in optimising the performance of the current ATM system.

A review of existing capacity estimation methodologies has been accomplished. The results of this review indicate that current en-route airspace capacity estimation techniques are fundamentally focused on ATCO workload: no methodology that accounts for the performance of the long-term planning, ASM and ATFCM functions has been identified.

In addition, the identified ATCO workload estimation techniques are focused on the initial concept development and the experimental design phases of the capacity estimation lifecycle. In order to estimate the capacity impacts during operational trials or real operations, the existing techniques are unable to capture individual ATCO strategies and require large post-operations tasks.

These findings lead to the necessity of a new en-route airspace capacity estimation framework able to account for the relevant en-route airspace capacity factors identified in CHAPTER 3 and overcome the deficiencies encountered of ATCO workload estimation techniques.

Based on these limitations a novel capacity estimation framework has been proposed in this section. This framework aims to overcome all the mentioned limitations by proposing a 4-step framework.

The next chapters (CHAPTER 5 to CHAPTER 9) develop, evaluate and validate each of the framework areas whereas CHAPTER 10, discusses the complete implementation of the framework from Step 1 to Step 4.
CHAPTER 5  THE CAPACITY AND COST-EFFICIENCY TRADE-OFF

The objective of this chapter is to develop the cost-efficiency framework area.

As discussed at the end of Chapter 4, airspace capacity is related to the cost-efficiency of an ACC. Capacity and cost-efficiency are two dependent magnitudes and an increment in one of them can lead to a decrement in the other and vice versa. The scenario in which only the minimum required staff to meet the optimum airspace configuration requirements is planned corresponds to an optimum trade-off between capacity and cost-efficiency (Tobaruela et al., 2013).

This chapter addresses the trade-off between these two factors. It starts with an identification of ACC cost-efficiency drivers (Section 5.1). Section 5.2 develops a methodology for the quantification of an ACC’s cost-efficiency. This methodology is applied to two different ACCs in Europe: MUAC (Section 5.3) and Geneva Upper Area Control (GUAC) (Section 5.4). The first case study shows the interdependencies between the variables that build up the ACC cost-efficiency whilst the second case study explores the relationships between cost-efficiency and airspace capacity shortages.
Section 5.5 presents the findings and discusses the effects that the SESAR OIs will release in the future ATM system.

### 5.1 Operating Cost-Efficiency Drivers

Cost-efficiency is a major consideration for national and international authorities in today’s air traffic scenario in Europe. Regulations are being placed to avoid over-expenses e.g. Regulation Period 1 (Commission, 2011).

Cost-efficiency assessments are usually conducted by regulatory authorities and ANSPs to increase competitiveness. These have an economic costing approach as they are undertaken to evaluate the profitability of the ATC centre. For this kind of analysis a thorough characterisation of the costs of providing air traffic services and the revenue generated by the air traffic is required. ACC costs include operating costs, depreciation and costs of capital. The main source of income for an ACC is from route charges (SESAR, 2008a, PRC, 2012).

This interrelation between capacity and cost-efficiency has already been captured in (EUROCONTROL, 2007). This study identifies that the optimum operating strategy for an ACC is that in which the costs associated with the creation of capacity are minimum. However, it fails to capture that the creation of capacity or the reduction of the costs associated with capacity shortages can be achieved as well with an enhanced performance of the planning process and the ASM function, which allow a high sustained capacity, as discussed later in this chapter. Other studies such as (Nero and Portet, 2007, Veronese et al., 2011), which share an economic costing approach, fail to capture the operating cost-efficiency drivers.

This chapter focuses on the cost-efficiency associated with operational factors i.e. the cost-efficiency resulting from the management of staff and the prevention of delays. Therefore, it only considers ATCO staff and not the rest of the support staff such as engineers. The cost-efficiency analysis assesses the daily operations of ACCs. Within the daily time-frames, the remaining ACC costs (depreciation and costs of capital) and routes charges are assumed to be invariable.

Therefore, given the assumptions above and in order to accurately estimate the ACC
operating cost-efficiency (or simply cost-efficiency) it is necessary to understand the drivers that make the management of ATCOs efficient.

5.1.1 The planning process and Airspace Management

The ATCOs on duty on a given day of operations are planned several months in advance as part of the long-term planning function (Section 2.3.4). The long-term plan is generated to fulfil ATCO contractual agreements, which state the anticipation with which ATCOs need to know the future shifts that they will be working.

The daily workforce plan of ATCOs aims to provide sufficient workforce to man all operational sectors that are planned to be opened according to the traffic estimations throughout the day. This plan can evolve over time, although the ATCO workforce remains invariable once the daily ATCO roster has been published.

Typically, the larger the anticipation of the plan to the actual execution leads to increased uncertainty associated with the plan. Uncertainties include traffic demand, the distribution of demand over the day, unforeseen scenarios (e.g. system failure), weather impact, intense military activity or ATCOs unforeseen shortages (sickness, delays and “no-shows”). In order to account for these uncertainties, the plans introduce buffers that prevent staffing shortages.

Even though these buffers provide robustness and the ability to respond to unforeseen scenarios, they are a potential source of cost-inefficiency. In this chapter it is hypothesised that the buffers are larger for increasing LATs, when the uncertainties are more acute.

During operations, the most appropriate airspace configuration is chosen by the ASM function to provide sufficient capacity to the airspace users. The selection of the airspace configuration is made according to short-term predictions (around 1 hour LAT) on air traffic demand and ATCOs availability. Ideally, the ASM function selects the airspace configuration that provides sufficient capacity whilst making optimal use of ATCOs. Underused operational sectors indicate a poor cost-efficiency performance.

The partition of the airspace into smaller portions (airspace sectors) increases the airspace capacity (Section 2.3.3). However, this split of the airspace implies a more intensive use of
the ATCOs since more operational positions need to be manned. As a consequence, ACCs have to optimise their workforce ensuring that a sufficient number of ATCOs is available to meet the required airspace capacity, without being excessive.

When the number of ATCOs is insufficient, air traffic delays occur. Delays in Europe are classified in groups depending on the source from which the delay originated: weather events, capacity, special events, ATC disruptions and staffing insufficiency. Staffing insufficiency occurs when an insufficient workforce is planned for operations. In 2011, 25.3% of total en-route delay in Europe was due to staffing shortages (Manager, 2012).

In summary, the operating cost-efficiency of the ACC depends upon the performance of two separate drivers:

- The planning process.
- The ASM function execution performance.

The section below develops a methodology to assess each of the two drivers and estimate the overall operating cost-efficiency of the ACC.

### 5.2 A Methodology to Estimate ACC Cost-Efficiency

The methodology developed in this section estimates the ACC cost-efficiency by analysing the accuracy of the planning process and the performance of the ASM function. An assessment solely based on the performance of the two drivers independently would not provide a good indication of the cost-efficiency.

This approach to ACC cost-efficiency, rather than an economical one (e.g. returns on operational expenditure) is based on operating parameters. In financial terms, other factors such as the number of working days per ATCO and the cost of each ATCO is included in the analysis as in (PRC, 2003).

A necessary, but not sufficient condition for a cost-efficient ACC performance is a very accurate planning process in which the resources planned during the months prior to the execution day coincide to the resources used on the day of operations. In fact, it could occur
that the number of sectors open match to those planned in advance, but if these sectors are
generally unloaded, the ACC cost-efficiency would be consequently reduced.

On the other hand, a necessary but not sufficient condition for a cost-efficient ACC
performance is an efficient ASM performance with an optimum selection of the most
appropriate airspace configuration. For instance, the airspace configuration selection may be
optimum but ATCOs on duty may not actually be available.

Therefore, the approach of the methodology proposed in this thesis reflects the combined
effect of both operating cost-efficiency drivers, using three steps:

1. Calculation of the ACC planning accuracy (resource allocation).
2. Assessment of the performance of the resources (ASM execution performance).
3. Assessment of the overall cost-efficiency (resource allocation and ASM execution
   performance).

Sections 5.2.1, 5.2.2 and 5.2.3 address these steps respectively.

5.2.1 Calculation of the ACC planning accuracy

No attempts to quantify the accuracy of the ACC planning process have been found in the
literature prior to (Tobaruela et al., 2013). This section introduces a set of metrics for the
quantification of the accuracy of the planning process. The metrics, which are explained in
the sub-sections below, are specifically created to measure the accuracy for each of the stages
of an ACC evolutionary planning process, such as the one by MUAC.

The aim is to quantify the accuracy of the planning process in the ATCO-resource allocation
task. This quantification involves the following:

- Identification of planning buffers.
- Identification of the evolution of the planning accuracy as a function of the LAT.
- Identification of planning process strategies including seasonal planning strategies.
5.2.1.1 The ACC planning process

The ACC planning process is defined here as the process by which the available ACC resources (ATCOs) are allocated to ensure a delivery of air traffic services without incurring delays.

The planning process varies between ACCs. In general terms, the planning process can be either a strategic adaptive process or a rigid process (De Neufville, 1991). In the former, the plan for the day of operations dynamically changes according to the estimations made during different time-frames whilst in the latter, the initial plan is rarely amended.

Typically, the initial plan for the day of operations is submitted months before the day of operations to allocate ATCOs working shifts in advance. Within this time-frame, the uncertainty of the estimate used to make the plan is high, leading to potential planning inaccuracies. These inaccuracies may lead, in turn, to capacity shortages and cost-inefficiencies.

The accuracy of the planning process can be captured in terms of:

- The LAT, when the plans are elaborated i.e. the planning process stages.
- Accuracy of the estimation of the required resources compared to actual requirements.

There are two main magnitudes that are used for the characterisation of the planning accuracy: the Sector Opening Times (SOT) and the Operational Roster Times (ORT), as discussed below.

5.2.1.2 Sector Opening Times

The SOT is defined as the total amount of time of open sectors during a day and is measured in units of time:

\[
SOT = \sum_{j=1}^{n} Time\ open_{sector_j} \tag{5-1}
\]

where “n” is the total amount of operational sectors.
In order to compute this metric, the airspace configuration timeline for each day is needed. The configuration timeline reflects the start time and end time of a given airspace configuration. For instance, if the airspace configuration timeline is just one open sector throughout the day, the total time of open sectors for the day, or in other words the SOT would be 1 sector x 1440 mins/day = 1440 minutes.

At ACCs the SOT can be easily calculated throughout the planning process since the configuration timeline is accessible throughout the process. This allows for a comparison between the estimations and the actual execution, yielding the planning accuracy.

5.2.1.3 Operational Roster Time

The SOT reflects the amount of sector open time for a given day. Each of the open operational positions is manned by two ATCOs. However the amount of ATCO time used on a given day does not directly correspond to double the SOT. Extra ATCOs are planned to account for any unforeseen events. Additionally, ATCOs have breaks during and rigid time shifts that not necessarily match the airspace configuration timeline.

Therefore, a crucial magnitude for the study of the planning process accuracy is to identify how much ATCO-time is planned to be spent on position as stated by the shift assignment for the day. This ATCO-time is the ORT:

\[ ORT = \sum_{j=1}^{n} Time\ shift_j \]  

[5-2]

where “n” is the total number of shifts.

The planned SOT and ORT at each stage of the planning process should be very similar if accurate plans are to be achieved. Ideally, the relationship between the SOT and the ORT should be:

\[ SOT = \frac{ORT}{2} \]  

[5-3]

[5-3] indicates that the ideal situation at any stage of the planning process, given the planning errors due to the uncertainties of the prediction, is to plan exactly as much ATCO workforce
as necessary to open as much sector-time as indicated by the SOT.

In [5-3] the ORT is divided by 2, since each minute of SOT corresponds to two minutes of ORT (two ATCOs per operational sector). However, this ideal relationship is rarely achieved due to the existence of planning buffers, the flexibility of the roster and overstaffing. These three components are introduced in the following paragraphs.

- Planning buffers

Planning buffers are introduced in order to allow for an additional workforce in case the SOT required at the end of the planning process is larger than the estimation in previous stages. As mentioned in Section 5.1, the ATCO workforce is fixed once the roster is published and therefore no change can be carried out to the ORT. Moreover, when unforeseen staffing events occur, such as sickness, a workforce back-up is needed to cover the manpower loss.

- The flexibility of the roster

The roster is formed of several shifts of fixed start time and duration. During these shifts, ATCOs take breaks, and these can be dynamically scheduled within the shift according to the traffic needs i.e. if a lot of demand is expected and ATCO use is estimated to be intensive, the breaks can be postponed until a later stage in the shift. However, there are limitations to the extent to which shifts can be dynamically managed (e.g. ATCOs should have 2 hours break per shift) and these limit the roster flexibility.

In order to ensure adequate levels of staffing able to accommodate short-term variations of traffic, staff beyond the nominal optimum is required.

- Overstaffing

(Grebenšek and Magister, 2012) identified the effect of overstaffing and its associated seasonal cycles in the ACC cost-efficiency. Results show that the calculation of the cost-efficiency highly depends on the season. The study assumes cost-efficiency solely as a function of unexploited resources during the valley traffic season i.e. winter. However, this is an oversimplified approach as it does not capture the rest of the ACC cost-efficiency drivers.
listed in Section 5.1.

During periods when the available staff is larger than needed to meet the demand requirements (typically winter), ATCOs are still called on duty due to contractual agreements. In fact, based on the contractual agreements they are entitled to select when they desire to work and leave on holidays. In addition, in order to maintain the ATC licenses ATCOs have to work a minimum number of hours. The result is an ATCO overstaffing during the low traffic seasons of the year.

Due to these three factors, typically the ORT is overestimated with respect to the SOT for each stage of the planning process. This hypothesis will be later confirmed in Section 5.2.1.8.

A set of metrics to capture the evolution of the accuracy of the planning process based on ratios between SOTs and ORTs is developed in (Tobaruela et al., 2013). They were developed to specifically measure the accuracy of a general evolutionary planning process e.g. MUAC.

The metrics introduced below have been developed to describe a hypothetical planning process of two stages followed by the execution. The 1st stage corresponds to the long-term development of the roster and the initial plan whilst the 2nd stage corresponds to pre-tactical LATs, i.e. hours before execution.

5.2.1.4 Airspace Planning Efficiency

Airspace Planning Efficiency (APE) is a measure of the accuracy of the first plan published at the end of the 1st stage in relation to the actual execution:

\[
APE = \frac{SOT_{\text{Exec}}}{SOT_{1\text{st stage}}} \tag{5-4}
\]

The APE captures the inaccuracy of the airspace configuration timeline at the 1st stage compared to the actual execution. The SOT_{1\text{st stage}} is in turn used to make the estimation of the total amount of ATCOs needed i.e. the ORT. Therefore SOT_{1\text{st stage}} and the APE are key
indicators for the cost-efficiency.

However, the ORT hardly corresponds to the SOT\textsubscript{1st stage} as it was already mentioned above due to the presence of three factors: the overstaffing issue, flexibility of the roster and the presence of buffers. The metric below captures the ORT overestimation.

### 5.2.1.5 Operations Roster Time Buffer

The operations Roster Time Buffer (Δ\text{ORT}) represents the deviation introduced in the ORT estimation at the 1\textsuperscript{st} stage. This metric is extremely relevant due to the fact that the SOT\textsubscript{1st stage} and the ORT should ideally be equal (see [5-3]) since they are both published at the same time with the same levels of uncertainty. However, this is very rarely the case as it will be later seen in this chapter and Δ\text{ORT} captures this difference:

\[
\Delta_{\text{ORT}} = \frac{\text{SOT}_{1\text{st stage}}}{\text{ORT}/2} \tag{5-5}
\]

### 5.2.1.6 Planning Refinement Ratio

The Planning Refinement Ratio (PRR) metric captures the effect of the planning process updates introduced during the longest phase of the planning process before the introduction of short-term information on the day of operations (from 1\textsuperscript{st} to 2\textsuperscript{nd} stage):

\[
\text{PRR} = \frac{\text{SOT}_{2\text{nd stage}}}{\text{SOT}_{1\text{st stage}}} \tag{5-6}
\]

A large deviation from PRR=1 indicates large changes to the SOT between the 1\textsuperscript{st} and the 2\textsuperscript{nd} stages. PRR>1 reflects a reduction in the SOT metric between the 2 metrics i.e. SOT was initially over-estimated, whilst PRR<1 reflects the opposite phenomenon.

### 5.2.1.7 Pre-Tactical Planning Efficiency

The Pre-Tactical Planning Efficiency (PPE) is an indication of the accuracy of the 2\textsuperscript{nd} stage compared to the actual execution:
\[ PPE = \frac{SOT_{\text{Exec}}}{SOT_{\text{2nd stage}}} \]  \[5-7\]

The PPE metric reflects the inaccuracy of the pre-tactical stage of the planning process compared to the actual execution. PPE values above 1 indicate an under-estimation of the SOT in the pre-tactical phase, which may arise safety concerns.

### 5.2.1.8 Overall Planning Efficiency

The Overall Planning Efficiency (OPE) is similar to the APE, although OPE focuses on the ORT instead of the SOT\textsubscript{1st stage}. OPE represents the ratio of ATCO time being used to what was estimated during the 1\textsuperscript{st} stage through the ORT publication:

\[ OPE = \frac{SOT_{\text{Exec}}}{ORT/2} \]  \[5-8\]

An OPE value of 1 shows that the staffing plan made during the 1st stage was accurate and that all the ATCOs planned in the roster were actually used on the day of operations. When OPE overshoots 1, the executed SOT is larger than the available ATCOs to man all the operational positions (ORT/2). Theoretically, this situation can never occur since there are no spare ATCOs available for the day of operation other than those planned and reflected in the ORT. However, eventually when extra ATCOs are needed this can be provided by means of:

- ATCOs voluntarily working extra time (extended shift length).
- EOS working as ATCOs.
- Use of ATCOs in stand-by duties. A stand-by duty is created as a back-up resource of additional ATCOs, which can be called on duty if workforce shortages occur.

When no additional ATCOs can be used through any of these three means, a staffing regulation must be put in place, leading to capacity shortages.

The case where OPE is below 1 corresponds to cost-inefficiencies in the planning process. The \( SOT_{\text{Exec}} < ORT/2 \), hence there is a part of the workforce which is not actually being used.

In summary, the OPE metric is able to capture the trade-off between planning accuracy and capacity with values over 1 corresponding to capacity shortages and values below 1 corresponding to cost-inefficiencies.
corresponding to cost-inefficiencies.

OPE can further be expressed as:

\[
OPE = \frac{SOT_{\text{Exec}}}{SOT_{\text{2nd stage}}} \cdot \frac{SOT_{\text{2nd stage}}}{SOT_{\text{1st stage}}} \cdot \frac{SOT_{\text{1st stage}}}{ORT/2} = \Delta ORT \times PRR \times PPE = \Delta ORT \times APE
\]  

[5.9]

and captures the inefficiencies associated with each of the steps of the planning process. As previously discussed, the sources of these uncertainties correspond to the uncertainty of the estimations made during the planning process or the structural inefficiencies of the roster and the workforce.

\[
OPE = f(\text{overstaffing, uncertainty})
\]  

[5-10]

The second driver for cost-efficiency is the ASM execution performance. This is assessed in the next section.

### 5.2.2 Airspace Management execution performance assessment

The metrics presented in the previous section estimate the accuracy of the planning process in terms of the resources allocated at each planning stage with respect to the resources used on the day of operations.

The actual resources used during operations, measured by the executed SOT, are impacted by the ASM function performance. Its performance can affect the cost-efficiency of the ACC regardless of the planning process accuracy.

It is thus important to quantify the performance of the ASM function. This assessment is based on the results obtained in (Tobaruela et al., 2015).

As discussed in Section 2.3.3, the primary objective of the ASM function is to manage the airspace configuration on the basis of the available resources to offer a capacity tailored to the demand. According to (ICAO, 2011), ASM is “the process by which airspace options are selected and applied to meet the needs of the airspace users”. This definition of the ASM function implies that the main objective is not cost-efficiency but to provide the user with the requested needs. Therefore, the targeted ASM performance will not necessarily be the most
cost-efficient.

Being cost-efficient has traditionally been measured through the ratio traffic/ATCO (Nero and Portet, 2007). Taking as an example the Brussels sector group at MUAC in Figure 5-1, the airspace configuration with the highest traffic/ATCO ratio can be seen to be the one-sector airspace configuration (Figure 5-2).

![Figure 5-2 Cost-efficiency as a function of the number of sectors for MUAC Brussels sector group](image)

In Figure 5-2 the transition from an airspace configuration with a given number of sectors e.g. two sectors, to a configuration with an additional sector (three sectors) is produced when the traffic reaches the average OTMV for all the airspace configurations with the given number of sectors open (two sectors). The average OTMV for a given number of open sectors is calculated as the average OTMV for all the sectors present in the available airspace configurations (“n”) which have an open number of sectors equal to “s” [5-11]:

\[
\frac{\sum_{i=1}^{n} \sum_{j=1}^{s} OTMV_{i,j}}{n \times s}
\]  

[5-11]

Once the sum of the occupancies of all the operational sectors exceeds the calculated average OTMV as in [5-11], it is assumed that an additional operational sector is required, therefore
moving in Figure 5-2 to the region of airspace configurations with one more operational sector.

This is a simplification of real operations as the inability of available airspace configurations to meet demand may not be corrected through the addition of an additional operational sector. This typically occurs when the saturation is localised in the centre of an airspace volume that cannot be split using more than one operational sector.

Nevertheless, Figure 5-2 is able to reflect that the use of configurations with higher number of operational sectors, which increase the available capacity, has in turn a negative effect on the traffic/ATCO ratio. In fact, the best airspace configuration from a cost-efficiency point of view is that with a single operational sector.

In real operations, apart from night times, it is very rare to use a single operational sector airspace configuration. This occurs since the ASM function objective is not uniquely aimed at cost-efficiency. In fact the ASM function has the following objectives which are captured in (Gianazza et al., 2009):

1. Ensure no over-deliveries.
2. Maintain delay to a minimum.
3. Maximise traffic load per operational sector.
4. Balance workload between operational positions.

The approach used in this methodology assesses the performance of the ASM function in cost-efficiency terms but also from the perspective of the three remaining objectives. This integrated approach avoids obtaining biased results i.e. the accomplishment of one objective may have a negative effect in other objective.

A widely extended indicator of operational cost-efficiency is the traffic/ATCO ratio that quantifies to what extent ATCOs are being active. The higher this ratio, the better the use made of the ATCOs, and hence the more cost-efficient the operation. However, the traffic/ATCO ratio is not solely a function of the ASM function performance, and can therefore show low values even when the airspace and resources are being optimally managed.
As previously discussed, a poor performance of the ASM function yields low traffic/ATCO values. However, this ratio is not only a function of the ASM performance. It also depends upon other factors as discussed below:

\[
\frac{\text{Traffic}}{\text{ATCO}} = f(\text{ASM}, \text{capacity}, \text{airspace design}, \text{complexity}, \text{demand})
\]

Each of the factors is further classified as a control or non-control variable in terms of the ability to act during operations to enhance the traffic/ATCO ratio.

- **ASM function performance**

An imbalanced allocation of resources given the demand requirements is a major factor contributing to a low traffic/ATCO ratio. The resources allocation is performed by the ASM function.

The ASM function performance is defined as a variable of control in the traffic/ATCO ratio since it is possible to actively act upon it during operations to optimise such ratio.

- **Capacity**

The maximum capacity of the operational sector defines the maximum safe value of the ratio. When the ratio exceeds its maximum, traffic over-deliveries are occurring. The ratio will vary as a function of structural characteristics such as the size and the maximum capacity (Section 3.3.4), leading to differences in the traffic/ATCO ratio.

The capacity factor is defined as a non-control variable as it is not possible to act upon it during operations in order to obtain an enhanced ratio value.

- **Airspace design**

An inadequate airspace design can potentially reduce the traffic/ATCO ratio. If there are no available airspace configurations able to increase the capacity in a congested airspace volume, the ratio will be low even when the ASM function performance is optimal and has selected the best available airspace configuration.
The quality of the airspace design is defined as a non-control variable since the airspace design is fixed during operations.

- Complexity of the traffic scenario

As introduced in Section 3.4.1 the complexity of the traffic scenario can lead to increased ATCO workload and may consequently require a reduction in the demand. However, the reduction of the ratio due to the complexity of the traffic scenario should not be associated with a poor cost-efficient ACC performance.

The complexity of the traffic scenario is defined as a non-control variable since it is assumed that the complexity is directly linked to the demand characteristics and the structural complexity of the airspace.

- Air traffic demand

In very low air traffic demand scenarios, even the one-sector airspace configuration will show low traffic/ATCO values. This occurs not because of an incorrect ASM function performance but due to a lack of air traffic demand. This situation is typical during night times.

The demand is given by the airspace users preferences and cannot be changed from the ACC, therefore this is considered a non-control variable.

Whilst the ASM function is a control variable that can be optimised to enhance the traffic/ATCO ratio, the rest of the variables are non-control variables i.e. it is not possible to act upon them to obtain better traffic/ATCO values.

The aim of this analysis is to identify to which extent the available operational control variables are being used to enhance the traffic/ATCO ratio. Since the non-control variables cannot be used to optimise it, a cost-efficient ACC performance is defined as the optimum performance of the ASM function that yields the best possible traffic/ATCO value given the rest of the non-control variables. Therefore the effect of the ASM function on the traffic/ATCO needs to be isolated from the effect of the non-control variables.
In order to determine the marginal contribution of the ASM function performance in the ratio, the ideal methodology is to find the instantaneous best airspace configuration for each combination of the rest of the factors. The instantaneous optimum airspace configuration is the one providing the maximum traffic/ATCO ratio given a combination of maximum capacity, airspace design, complexity and demand.

The identification of the optimum airspace configuration has been the focus of several studies. (Gianazza et al., 2009) develop a methodology to calculate the optimum sector configuration for French airspace based on traffic predictions and ATCO workload estimations. In their analysis, the cost of an airspace configuration is computed as the “the number of overloaded, under-loaded and normally loaded“ operational sectors. (Bloem and Kopardekar, 2008) develop a heuristic algorithm to quantify the number of open basic sectors that can be combined to increase the cost-efficiency, with the aim to support the strategic airspace design of the ACC.

These studies contribute towards improving the operational cost-efficiency performance. However, they do not provide an overall cost-efficiency measurement framework. An accurate analysis has to identify the effects of an optimised ASM function performance from a cost-efficiency perspective on the rest of the ASM objectives. As discussed before, the main objective of the ASM function is not to be cost-efficient, but instead to provide the airspace users with the means to carry out their operations with minimum disruptions. Therefore an optimum ASM function performance would maintain delays to a minimum and find a trade-off between the remainder of the three objectives.

As already mentioned above, this thesis uses an integrated approach between the four ASM objectives in order to avoid biased results on the cost-efficiency analysis. Within this approach four metrics are introduced, which assess the performance of the ASM function in achieving each of the four ASM objectives. These metrics are utilisation, over-deliveries, staffing delays and sector traffic imbalance.

5.2.2.1 Over-deliveries

The over-delivery metric is associated with the achievement of the first ASM objective. An over-delivery is defined as a situation in which the traffic demand exceeds the OTMV. This
objective is associated with the safety KPA, since an excessive traffic demand can have negative effects on the ATCO workload levels. The over-delivery is mathematically expressed as:

\[
\text{Overdelivery}_{\text{day}} = \sum_{i=1}^{n} [(\text{actual occupancy} - \text{OTMV}) \times \text{duration}]_i
\]  

[5-13]

where “n” represents each instant during the day. Depending on the definition of occupancy (e.g. one-minute or ten-minutes occupancy) “n” will vary (e.g. n=1440 or n=144 respectively).

In [5-13] the magnitude of the over-delivery depends on the value of the occupancy overshooting and its extension over time. Therefore, the larger the occupancy excess and the larger this excess is prolonged over time, the more severe the over-delivery results will be. The metric units are flights x seconds.

5.2.2.2 Staffing shortages

This metric is associated with the second ASM objective. Staffing delays occur when there is an insufficient workforce to man the optimum airspace configuration. Although staffing shortages can be produced due to insufficient planned staff, the manner in which the available resources are managed during the day of operations can have an impact on the generation of staffing-induced delays.

For instance, if ATCOs are intensively used during times when they are not needed, when more demanding traffic scenarios occur, these ATCOs would no longer be available for active duty. The ASM function has to ensure that the workforce is strategically managed in order to ensure that the available workforce is available to man the optimum airspace configuration at each moment in time.

Staffing delays are measured in units of time (usually minutes) and can be accessed by request to the Eurocontrol Network Manager.
5.2.2.3 **Utilisation**

The utilisation metric or traffic load used here is associated with the third ASM objective. (Bloem and Kopardekar, 2008) define utilisation as an indicator of the use of the available airspace capacity. The utilisation metric used here is the average use of the available capacity each minute for any given operational sector [5-14]:

\[
Utilisation_{day} = \frac{1}{1440} \sum_{i=1}^{1440} \left( \frac{1}{n} \sum_{j=1}^{n} \frac{Occupancy_{i,j}}{OTMV_{j}} \right) \quad [5-14]
\]

where “i” is the time of the day (1440 minutes in a day) and “j” the number of open operational sectors at a given time.

The lower the value of this metric, the less use of the available resources is being made, therefore the more cost-inefficient the operations.

This metric also incorporates structural or airspace design and traffic flow factors. For example, if there are only 9 flights in an operational sector with a maximum occupancy of 18, the optimum configuration is one sector, although the traffic load (9/18) would suggest that the efficiency of the configuration is just 0.5 i.e. the ASM performance is optimal but the efficiency is only 0.5.

In order to rule out the airspace configuration effect, during the data analysis performed in future sections, airspace configurations with only one operational sector (typically associated with low traffic scenarios during the night) have been removed.

5.2.2.4 **Sector traffic imbalance**

This metric is associated with the achievement of the fourth ASM objective. This is defined as the dispersion of the traffic load across all the operational sectors from the average traffic load in the operational sectors. This is calculated by the standard deviation of the operational sectors:

196
\[ Imbalance_{day} = \frac{1}{1440} \sum_{i=1}^{1440} \sqrt{\left( \frac{1}{n} \sum_{j=1}^{n} \left( \frac{Occupancy_{i,j}}{OTM_{j}} - \left( \frac{1}{n} \sum_{j=1}^{n} \frac{Occupancy_{i,j}}{OTM_{j}} \right) \right)_{i} \right)^2} \]  

[5-15]

A traffic imbalance equal to zero indicates optimum balancing between the operational sectors.

### 5.2.2.5 Airspace Management execution performance calculation

The four metrics identified above individually describe the performance of the ASM function in each of their associated ASM objectives. However, from the individual analysis of the metrics, no conclusion can be drawn on the overall ASM performance. A metric is developed in (Tobaruela et al., 2015) that provides insight into this overall performance: the ASM Execution Performance (AEP).

The AEP corresponds to the area enclosed by the four-side polygon in Figure 5-3. This polygon is formed by four axes each of them proportional to each of the four metrics identified above.

The AEP value is normalised to an area of two units, which is defined as the optimum AEP value, and corresponds to the optimum performance of the four individual metrics.
A larger AEP value is due to a better performance of each of the four individual ASM performance metrics. The external rhomboid represents the maximum AEP, result of an optimum performance of the four individual metrics.

The polygon area in Figure 5-3 for the AEP measurement assumes that all the factors are equally weighted and contribute equally to the overall metric. This assumption is made based on discussions with FMPs from MUAC. Three FMPs were asked about the relative importance of the four metrics that represent the four ASM objectives.

The results from these discussions indicated that over-deliveries (ASM safety objective) stand out from the other three objectives. However, the FMPs stated that in current ATC operations traffic over-delivery occurs very frequently and usually are not associated with a safety degradation i.e. they are perceived as normal-operations, even though it is preferable to avoid them. FMPs discuss with ATCOs in the operational sectors the possibility of producing
a temporal over-delivery, in order to avoid opening additional operational sectors. The ATCO evaluates if this over-delivery, given the complexity associated with it that is communicated by the FMP, can be safely handled.

5.2.3 Overall Cost-Efficiency

As previously discussed, the OPE alone is not a reliable indicator for the ACC cost-efficiency because it does not capture the performance of the ASM function e.g. it does not capture whether additional sectors are the result of increased demand or simply due to overstaffing. Similarly, the execution performance of the ASM function does not provide a clear indication of the cost-efficiency because it does not capture how many resources were allocated for that day.

The Overall Cost-Efficiency (OCE) metric overcomes these issues by combining the effects of the planning process accuracy and the cost-efficiency performance of the ASM function (Figure 5-4).

Figure 5-4 Computation of the OCE metric

The OCE corrects the OPE value through the utilisation metric, which indicates to what
extent the open airspace sectors are being loaded [5-16]. This metric provides a real indication of the operational cost-efficiency of the OPE, from the early stages of the planning process until the execution.

\[ OCE = OPE \times Utilisation \]  

[5-16]

The two sections below apply this methodology to the MUAC and GUAC centres. The methodology is first applied to the MUAC and due to the limited relevance of its results due to the nature of MUAC operations the same analysis is achieved for the GUAC to overcome some of the deficiencies encountered during its first application at MUAC.

5.3 MUAC Case Study

The methodology developed in the previous section to assess the cost-efficiency is applied in the current section to the MUAC. The methodology is applied in a three-step process: characterisation of the accuracy of the planning process, quantification of the ASM function execution performance and finally computation of the OCE.

MUAC planning can be defined as a strategic layered process. It is formed of 4 stages before the execution:

• 1st stage

During this stage, the required ATCO time needed (ORT) and the airspace configuration timeline for the day are determined. These estimations are based on the analysis of traffic forecasts and available resources. This is referred to as the Master phase at MUAC. The ORT corresponds to the maximum time that the ATCOs can work in a day as stated by the shift i.e. the length of the shift. Other tasks within the ACC, such as training and office duties, or sickness leave, are not included in the ORT.

The ORT is fixed after the publication at this stage, hence the number of ATCOs for a given day is known at least three months in advance, although the airspace configuration timeline may be subject to changes in subsequent stages.

• 2nd stage

200
This stage is similar to the 1st stage plan, however it additionally accounts for imbalances between the estimated SOT and planned staff. The specific ATCO shift assignment is published. This is known as the planning phase and the results are published two weeks prior to the day of operations.

- **3rd stage**

The 2nd stage plan is periodically updated including seasonal trends of traffic for the corresponding day of the week e.g. Tuesdays of preceding 2 weeks. Depending on the results of this assessment, flexible shifts are assigned at this stage. This stage is called pre-tactical phase and its results are published the day before the operations.

- **4th stage**

During this stage, the outputs from stage 3 are updated based on short-term information including weather and military activity. This, stage which produces the Daily Operations Plan (DOP) is called the Tactical phase and is published prior to the start of the day of operations.

During the ATC execution and based on the available staff and shift assignments, the EOS manage the airspace configurations (ASM function), combining and splitting sectors, in order to tailor capacity to demand. When the available workforce and shift assignments are not able to provide sufficient capacity, an ATFCM regulation may occur, i.e. capacity shortage. On the other hand, when the workforce is excessive, the ATCOs can arrive later (late-come) or leave early (early-go) than what is indicated by their particular shifts, hence not using the resources to their maximum extent.

Figure 5-5 depicts MUAC’s layered process and its outcomes during the different stages:
The MUAC planning process has evolved over time in order to allocate staff more accurately. This section identifies the drivers of the planning process evolution, and performs a before-after statistical analysis in order to quantify the effects that the evolution of this planning process has had on its accuracy.

The historical analysis conducted referred to the period from the opening of the centre (1972) to date (2013). However, due to data availability limitations the statistical analysis developed in this section only relates to the period from January 2009 to September 2012.

The aim of conducting a historical analysis is to identify which implementations have had a major effect on the planning process accuracy. This was accomplished through a review of internal MUAC documentation complemented by interviews of 15 SMEs including engineers and operational staff. These were semi-structured face-to-face interviews with the purpose of identifying if any of the historical implementations had had an effect on the performance of
the planning process.

The main changes that have affected the planning process are introduced below.

- The new roster

The new roster was gradually implemented over a four-year period between 2008 and 2011. The old roster formed of only five shifts was substituted by a new one incorporating a total of 24 shifts. With the new roster, shifts started every half an hour from 06:00 am until 17:00 pm.

The introduction of two novel shift types within the new ACC roster are direct contributors to the cost-efficiency of the centre:

  - The “flex-duty”: enables the assignment of the exact shift on the evening before the day of operations (publication of the 3rd stage of the planning process). This allows to refine the DOA, including short-term information without making major changes to the plan.
  - The “stand-by” shift: is a back-up shift created for ATCO replacement in case of non-planned absence e.g. sickness. This shift constitutes a back-up for avoiding regulations under unplanned staff shortages.

- The Statistical Prediction Tool (SPT)

This tool generates traffic estimates and consequently ORT predictions based on historical traffic analyses. Nevertheless, this tool was never fully operational due to the lack of trust in it by the EOS.

- Refinement of the planning process

The different stages of the planning process previously detailed are introduced to substitute a mostly rigid planning process. The periodic updates of the plan with increasingly reliable information will later be shown to be a key enabler of a more cost-efficient ACC performance.
• “TimeZone”

The *TimeZone* tool enables to dynamically optimise the available resources on the day of operations, capturing the airspace configuration plan for the day and the remainder of available resources for the rest of the day.

*TimeZone* changes the staff allocation in the ACC without changing the assigned shift but managing the duration and location of the breaks. This helps preventing the overuse of staff when not needed, keeping the workforce ready for when it may be needed.

• Central Supervisory Section (CSS)

The introduction of the CSS lead to a change in the EOS roles. Previously, sector group supervisors were responsible of locally performing the ASM function on each sector group (Brussels, DECO and Hannover). Following the introduction of the CSS, local sector group supervisors were removed and a single three-group supervisor called *Executive Duty Supervisor* or simply *duty supervisor* for the whole airspace was created. The aim was to optimise airspace operations as a whole rather than individually.

Along with the introduction of the duty supervisor, supporting roles for it were created, such as the tactical capacity manager in charge of advising the supervisor on the most adequate capacity measures to be applied, and the assistant supervisor supporting the supervisor routine tasks.

The FMP remained unchanged with the main objective of making the duty supervisor aware of any predicted capacity/demand imbalances.

These improvements are summarised in Table 5-1:
Table 5-1 MUAC major planning process related improvements

<table>
<thead>
<tr>
<th>Improvement name</th>
<th>Improvement type</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>New roster (flex-shift)</td>
<td>Gradual</td>
<td>2008-2009</td>
</tr>
<tr>
<td>SPT</td>
<td>Step change</td>
<td>January 2010</td>
</tr>
<tr>
<td>Refinement of planning process</td>
<td>Gradual</td>
<td>1st quarter 2010</td>
</tr>
<tr>
<td>TimeZone</td>
<td>Step change</td>
<td>March 2010</td>
</tr>
<tr>
<td>CSS</td>
<td>Gradual</td>
<td>March 2012</td>
</tr>
</tbody>
</table>

In order to quantify the effects of the planning process enhancements at MUAC a statistical analysis is carried out in the following section.

5.3.1 Planning process evolution accuracy assessment

The planning process evolution accuracy assessment is based on a statistical analysis that assumes the existence of a transition period after which the impact of the improvements in the ACC cost-efficiency becomes significant. The hypothesis is that significant performance differences will be found prior and post transition period.

From the findings summarised in Table 5-1, SMEs were asked during the semi-structured interviews to rank the importance of each improvement in terms of the impact that each one could have had on the performance of the planning process.

The SPT and CSS were ranked as low impact factors, whereas the new roster, the refinement of the planning process and the introduction of TimeZone were ranked as high impact factors. Consequently, March 2010 (see Table 5-1) was selected as the transition period, between the old and the new planning process.

Having identified the most important factors that may have had an impact on the enhancement of the planning process and the transition period after which the planning process performance is expected to have changed, this section quantifies the accuracy of the
planning process in MUAC using the set of metrics developed above.

MUAC airspace is formed of three civil sector groups: Brussels, DECO and Hannover. ATCOs from one sector group have only one ATC license to control the sectors in that sector group and not in another\(^4\). Therefore, resources from the different sector groups can only be allocated to that sector group and the planning process is achieved independently for each sector group.

The time period of the analysis is limited from January 2009 to September 2012. This limitation is associated with the earliest recording of the metrics used for the analysis, which coincides with the introduction of the New-Flight Data Processing System (N-FDPS). This section studies the effect of the evolution of the planning process in a single sector group. However, the selection of the sector group has to be thoroughly made. This selection is made accounting for the major events occurring during this period of time, which may introduce singularities in the data set and bias the results.

It is therefore necessary to select a sector group with no major variations in procedures or operations during the time period of analysis. Table 5-2 summarises the major MUAC events during the period analysed.

<table>
<thead>
<tr>
<th>Event name</th>
<th>Event type</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>HACO re-sectorisation</td>
<td>Airspace Design</td>
<td>January 2010</td>
</tr>
<tr>
<td>Ash Cloud</td>
<td>Weather</td>
<td>April 2010</td>
</tr>
<tr>
<td>Ash Cloud</td>
<td>Weather</td>
<td>May 2011</td>
</tr>
<tr>
<td>Olympics</td>
<td>Sport</td>
<td>July-August 2012</td>
</tr>
<tr>
<td>Holstein Sector Split</td>
<td>Airspace Design</td>
<td>July 2012</td>
</tr>
</tbody>
</table>

Table 5-2 indicates a major re-sectorisation in the Hannover and DECO sector groups in

\(^4\) A few ATCOs have licenses in in two sector groups although this is very rare and the license of the second sector group only enables the ATCO to control a small subset of all the available sectors.
January 2010. The re-sectorisation consisted in passing sectors from the former sector group to the latter. This is translated in a variation of the SOTs for each sector group not associated with a variation in the planning process but with the existence or removal of new sectors. Similarly, the Hannover sector group underwent another airspace redesign in July 2012, with the split of the Holstein sector. Due to these major changes, Hannover and DECO sectors groups are excluded for the analysis and the Brussels sector group is chosen for the present case study.

For the analysis of this sector group, days when major events took place are treated as outliers and excluded from the data set. The next paragraphs discuss the evolution of the different metrics of the planning process accuracy applied to the Brussels sector group in MUAC.

- PPE evolution

Due to the existence of planning buffers, which allocate additional resources in the earlier stages of the planning process, the PPE is expected to be below a value of one. The difference between the PPE value and one is correlated with the magnitude of the planning buffer at the third stage of the planning process (pre-tactical phase). This 3rd stage planning buffer is estimated in [5-17]:

\[
\text{planning buffer} = 1 - \mu
\]  

[5-17]

where "\( \mu \)" refers to the mean value.
Figure 5-6 shows a steady value of PPE below PPE=1. Prior to the transition period (March 2010), a seasonal behaviour in the PPE can be observed. This is due to the lack of refinement of the planning process before the transition period: the planned SOTs during the year were almost fixed regardless of the season or day.

Statistical analyses of the PPE distributions prior and post transition period show statistical significance between both distributions. The data shows normality for a 98% confidence level Kolmogorov-Smirnov tests for both data sets (p>0.2). F-test rejects the hypothesis that the distributions have equal variance (p≈0 at 95% confidence level). Finally, an unequal variances t-test performed at 95% confidence level show statistical differences between the mean values of the PPE distributions before and after the transition date (p≈0).

Table 5-3 summarizes the significant descriptive statistic values that indicate the performance of the PPE metric before and after the transition period, including the magnitude of the 3rd stage planning buffer.
Table 5-3 PPE evolution descriptive statistics

<table>
<thead>
<tr>
<th></th>
<th>$\mu_{\text{PPE}}$</th>
<th>$\sigma_{\text{PPE}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.89</td>
<td>0.07</td>
</tr>
<tr>
<td>After</td>
<td>0.92</td>
<td>0.07</td>
</tr>
<tr>
<td>3rd stage planning buffer (after)</td>
<td>1.0-0.92=0.08</td>
<td>-</td>
</tr>
</tbody>
</table>

In the 3rd stage of the planning process a buffer of 0.08 is observed after the transition date. This indicates an average overestimation of 8% of the staff at this planning stage. The PPE does not show seasonal behaviour after the transition date, suggesting that the 3rd stage plan accounts for seasonal trends.

The value of the 3rd stage planning buffer (0.08) is approximately equal to the value of $\sigma_{\text{PPE}}$ after the transition period (0.07). This indicates a very good accuracy of the ACC planning staff in accounting for the uncertainties observed during execution. In fact, more than one-sigma of the variation of the PPE metric is within the 0.08 planning buffer, meaning that around 84% (84.13th percentile corresponds to one-sigma in a normal distribution) of the plans at the 3rd stage of the planning process are below the PPE=1 threshold.

- PRR evolution

The PRR metric represents the amount of variation in the plan from the 1st to the 2nd stage of the planning process. Larger SOTs are expected to be planned at the 1st stage than at the 2nd stage, meaning that the buffer for larger LATs (1st stage) is larger than for closer LATs (2nd stage). In the same manner as in the PPE metric, the planning buffer is calculated using [5-17].
The evolution of the PRR metric shows the lack of existence of a planning buffer between these two stages. After the transition period $\mu_{PRR}=1.01$, thus there is no observed planning buffer between these two stages. For the computation of the statistical values in Table 5-4, PRR values below 0.6 (resulting from graphical inspection) are considered outliers:

Table 5-4 PRR evolution descriptive statistics

<table>
<thead>
<tr>
<th></th>
<th>$\mu_{PRR}$</th>
<th>$\sigma_{PRR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.94</td>
<td>0.06</td>
</tr>
<tr>
<td>After</td>
<td>1.01</td>
<td>0.05</td>
</tr>
<tr>
<td>$1^{st}$ to $2^{nd}$ stage planning buffer (before)</td>
<td>1-0.94=0.06</td>
<td>-</td>
</tr>
</tbody>
</table>

However, Figure 5-7 suggests the existence of a planning buffer of 0.06 before the transition date.

Kolmogorov-Smirnov tests of the PRR samples before and after the transition period for a 1% significance level fail to reject the null hypothesis that the samples come from normal distributions (p=0.02 for both samples). A subsequent F-test at a 5% significance level rejects the null hypothesis that both data samples (before and after) come from normal distributions with equal variances (p≈0). Therefore, assuming unequal variances for an un-paired t-test at a
5% significance level, the null hypothesis that both distributions come from the same distributions with equal means is rejected (p\approx 0).

Statistical tests show significant differences in the means of the PRR samples before and after the transition. Therefore, it can be concluded that the PRR planning buffer was removed after the transition period. This implies, that the enhancements of the planning process implemented during the transition, have had a positive effect on the accuracy of the planning process, removing the previous planning buffers between the 1st and 2nd stages.

- **Airspace Planning Efficiency (APE) evolution**

The APE metric is expected to be below APE=1. The 2nd stage planning buffer should theoretically be more conservative than any other planning buffer since after this stage the plan cannot be significantly amended prior to execution.

Table 5-5 APE descriptive statistics

<table>
<thead>
<tr>
<th></th>
<th>µ</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APE</td>
<td>0.84</td>
<td>0.06</td>
</tr>
<tr>
<td>3rd stage buffer</td>
<td>1-0.84=0.16</td>
<td>-</td>
</tr>
<tr>
<td><strong>After</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APE</td>
<td>0.93</td>
<td>0.07</td>
</tr>
<tr>
<td>3rd stage buffer</td>
<td>1-0.93=0.07</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 5-8 APE evolution
Figure 5-8 suggests the existence of a planning buffer, with APE steadily below APE=1. Moreover, this planning buffer shows different behaviour before and after the transition period. This behaviour is statistically assessed below for all data excluding APE outliers, considered to be values below 0.6 from graphical inspection.

The Kolmogorov-Smirnov test reveals normality at 5% significance level both for the pre-transition (p=0.2) and post-transition distributions (p=0.31). The F-test at a 5% significance level shows no significance (p=0.19). This result leads to an assumption of equal variances in an un-paired t-test at 5% significance, which subsequently shows statistical significance of the differences in the mean values prior and post transition period (p≈0).

Therefore, it can be statistically concluded that the implementation of the changes on the planning process lead to a reduction of the planning buffer. According to the values in Table 5-5 the planning buffer was reduced by 44%.

- $\Delta_{ORT}$ evolution

The $\Delta_{ORT}$ represents the additional amount of ATCO time allocated in the 1st stage of the planning process compared to the amount of ATCO time derived from the SOT plan. Overestimations of ATCO times are expected, leading to $\Delta_{ORT}$ values below 1. The difference between the $\Delta_{ORT}=1$ value and the actual $\Delta_{ORT}$ value is interpreted as an ORT staffing buffer. Given the enhancement of the planning process after the transition date, an increase in the $\Delta_{ORT}$ metric is expected.
Figure 5-9 depicts the evolution of the $\Delta_{\text{ORT}}$ metric. A seasonal variation is observed, with peaks during the summer season and lower values during the winter season. The low values of the metric are associated with overstaffing. Due to the stagnation of the air traffic demand and the continuous recruitment of ATCOs, overstaffing has become more significant in recent years (Table 5-6).

Table 5-6 Overstaffing evolution in MUAC measured in ATCOs/flight

<table>
<thead>
<tr>
<th></th>
<th>Minimum - Summer</th>
<th>Maximum - Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1.192</td>
<td>1.481</td>
</tr>
<tr>
<td>2012</td>
<td>1.382</td>
<td>1.941</td>
</tr>
</tbody>
</table>

Relative increase: +16% +31%

The available ATCO workforce in ACCs is constant (excluding new recruitments and retirements) throughout the year. This workforce is theoretically designed to meet the traffic requirements during the most demanding period of the year: the summer peak. During this period, traffic is the highest and at the same time, the ATCOs are entitled to take a minimum amount of days of holidays. Due to contractual agreements and ATC license requirements, ATCOs need to carry out their duties a certain number of days during the year, including during the winter when some may not be needed. This results into overstaffing (low $\Delta_{\text{ORT}}$)
every winter season.

The staffing buffer and the overstaffing inefficiency are estimated as:

\[
\text{Staffing buffer} = 1 - (\mu_{\Delta \text{ORT}})_{\text{summer}}
\]

\[
\text{Overstaffing inefficiency} = (\mu_{\Delta \text{ORT}})_{\text{summer}} - (\mu_{\Delta \text{ORT}})_{\text{winter}}
\]

Table 5-7 \(\mu_{\Delta \text{ORT}}\) for summer and winter periods (before transition values highlighted in grey)

<table>
<thead>
<tr>
<th></th>
<th>Summer (Jul-Aug)</th>
<th>Winter (Dec-Jan)</th>
<th>Staffing buffer</th>
<th>Overstaffing inefficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1.01</td>
<td>0.94</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2010</td>
<td>0.93</td>
<td>0.89</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>2011</td>
<td>0.90</td>
<td>0.75</td>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td>2012</td>
<td>0.92</td>
<td>0.85</td>
<td>0.08</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The relative maximum and minimum values of the \(\Delta \text{ORT}\) (Table 5-7) calculated as the average \(\Delta \text{ORT}\) during December-January (winter) and July-August (summer) exhibit a slight reduction between the period prior to and post transition.

Before transition period \(\Delta \text{ORT} > 1\) is observed for a significant (132) number of days (Figure 5-9). Values above 1 indicate that the ATCO workforce planned is lower than the workforce required to staff the airspace configuration timeline for the day (SOT). This can be due to two different reasons:

1. Since overestimation in the planning process is commonly applied, the ORT planned in the 1\(^{st}\) stage is lower than the SOT at that moment, otherwise workforce would not be used
2. The number of available staff is insufficient

Given that the traffic levels have dropped since the year 2009, it is not likely that the large positive \(\Delta \text{ORT}\) is the result of insufficient staff numbers. Therefore, it is assumed that due to the lack of a robust planning process, SOT values at the 1\(^{st}\) stage were not fully considered for planning purposes.
The average staffing buffer (Table 5-7) after the transition period is 0.08. This implies that the inefficiency of the roster and shifts and the uncertainty at this stage creates a 8% increase in ORT minutes compared to the planned SOT. The inefficiency associated with overstaffing is of the same order of magnitude. These results suggest that an increase in the efficiency of the planning process can be obtained by the following approaches:

- Increase the prediction accuracy of the required staffing needs.
- Address winter overstaffing.
- Increase the roster and shift flexibilities.

Whilst the first means in today’s ATM system is unlikely to release any significant benefit due to the large amount of uncertainties in the first stage of the planning process, the second and the third could potentially reduce the inefficiencies of the planning process. From an implementation perspective, due to the barriers imposed by the ATCOs contractual agreements, the third is expected to be the most feasible approach.

- OPE evolution

The OPE represents the ratio between the total number of ATCOs allocated and the SOT execution on the day of operation. This metric, which captures the individual effects of the remainder of the metrics introduced, is expected to have a behaviour which is the result of the individual behaviours. This includes:

- Enhancement of the metric after transition period.
- Seasonal behaviour (summer vs. winter).
Figure 5-10 OPE evolution

Figure 5-10 depicts the evolution of the OPE metric. The presence of the seasonal evolution is confirmed although no significant improvement in the stationary value of the metric is observed. In fact, the effect of overstaffing masks any other metric enhancement. The total inefficiency of the planning process which is driven by the OPE metric is calculated separately for the summer and the winter period due to the seasonality.

\[
\text{planning process inefficiency} = 1 - (\mu_{OPE})_{summer,winter}
\]  

Table 5-8 OPE and planning process inefficiencies for summer and winter periods (prior to transition values are highlighted in grey)

<table>
<thead>
<tr>
<th></th>
<th>Summer (Jul-Aug)</th>
<th>Summer inefficiency</th>
<th>Winter (Dec-Jan)</th>
<th>Winter inefficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>0.77</td>
<td>0.23</td>
<td>0.71</td>
<td>0.29</td>
</tr>
<tr>
<td>2010</td>
<td>0.81</td>
<td>0.19</td>
<td>0.66</td>
<td>0.34</td>
</tr>
<tr>
<td>2011</td>
<td>0.83</td>
<td>0.17</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>2012</td>
<td>0.80</td>
<td>0.20</td>
<td>0.75</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Due to the seasonal behaviour of the planning process accuracy, the total inefficiency associated with the planning process is dived in Table 5-8 for the summer and the winter period.
In [5-9], the OPE was shown to be a function of $\Delta_{\text{ORT}}$ and APE. Although the average APE after transition is very close to the optimal (1) $\Delta_{\text{ORT}}$ is rather low, especially during the winter season. As a result the OPE is rather low.

5.3.2 AEP assessment

The analysis of the ASM execution performance embeds the period from 1 March 2012 to 30 September 2012 (214 days), when data is available. The calculation of the metrics introduced in Section 5.2 is shown in Figure 5-11.

![Figure 5-11 AEP and its four functional metrics](image_url)

Individual assessment of each of the four functional metrics suggests variations in the metrics according to the day of the week. This is for instance the case for the over-delivery metric. A Mann-Whitney two-samples test (Hettmansperger and McKean, 1998) reveals a significant difference (p<0.01) between over-deliveries for weekend and week-days. On average, weekends over-deliveries overshoot week-days by +5468 flights x minute (Table 5-9).
<table>
<thead>
<tr>
<th>Day</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
<th>Sunday</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14358</td>
<td>10718</td>
<td>12692</td>
<td>11487</td>
<td>13161</td>
<td>16169</td>
<td>19577</td>
</tr>
</tbody>
</table>

This difference between weekends and week-days reveals different working procedures of the ASM function. During week-days and due to the military activity, occupancy limits are monitored more thoroughly and restrictions are put in place more rapidly than during weekends, thus leading to larger and more frequent over-deliveries.

This effect is shown in Figure 5-12. This figure depicts the weekly evolution of the executed SOT vs. traffic ratio. This metric indicates the extent to which each minute of open airspace sector is used to control air traffic. It is apparent from this figure that the airspace level of utilisation is larger in weekends.

![Figure 5-12 Comparison of executed SOT executed / traffic ratio for weekends and week-days in the MUAC Brussels sectors group](image)
The figure shows almost steadily larger executed SOT minutes per flight for week-days than for weekends. This means that during week-days more sectors are open for the same amount of traffic than during weekends. This reveals a closer demand/capacity monitoring.

[5-21] computes the effect of the military activity in the SOT/Traffic metric which results in an additional 6.3% of open sectors for a same amount of traffic.

\[
\frac{\mu_{\text{sot}}^{\text{traffic}}}_{\text{week-day}} - \mu_{\text{sot}}^{\text{traffic}}_{\text{weekend}}
\]

The main difference in the operations on weekends and during week-days is the presence of military activity from Monday to Friday. Military activity in the airspace sectors is a relevant factor adding to the complexity of the ATCO activity. The performance of the ASM function can have more significant safety implication than on less complex scenarios (such as on weekends). Therefore, in order to avoid over-deliveries which can lead to over-loads due to the presence of military activity, the ASM function applies larger safety margins during week-days than during weekends.

Subsequently, this effect is noted as well in the utilisation metric, with on average larger values on weekends than during week-days (Table 5-10).

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>0.58</td>
</tr>
<tr>
<td>Tuesday</td>
<td>0.57</td>
</tr>
<tr>
<td>Wednesday</td>
<td>0.58</td>
</tr>
<tr>
<td>Thursday</td>
<td>0.57</td>
</tr>
<tr>
<td>Friday</td>
<td>0.58</td>
</tr>
<tr>
<td>Saturday</td>
<td>0.60</td>
</tr>
<tr>
<td>Sunday</td>
<td>0.61</td>
</tr>
</tbody>
</table>

On the other hand sector traffic imbalance does not show different daily behaviour ($\sigma=0.01$ and $\mu=0.25$).
No conclusion can be drawn from the staffing delays due to its low occurrence (only two days generated delays during the 214 days period). The case study in Section 5.4 will investigate this metric further.

For the analysis period the average AEP is 0.38 (ASM performing at 38% of its full capabilities) with a standard deviation of 0.12. The performance on week-days (mean 0.40) is better than on weekends (mean 0.32) due to the effect of the reduced over-deliveries. This average value for AEP can be considered as low.

In Table 5-11 the staffing delays have been neglected due to its low occurrence. This multiple correlation analysis shows that over-deliveries are strongly correlated both with utilisation and imbalance. Whilst the utilisation of the sector increases, the sectors are closer to their capacity limit, making it easier to observe over-deliveries. Therefore the correlation with utilisation is expected. However the even stronger correlation between sector imbalances and over-deliveries is surprising.

<table>
<thead>
<tr>
<th>Over-deliveries</th>
<th>Utilisation</th>
<th>Imbalance</th>
<th>AEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-deliveries</td>
<td>1</td>
<td>0.54</td>
<td>0.61</td>
</tr>
<tr>
<td>Utilisation</td>
<td>0.54</td>
<td>1</td>
<td>0.43</td>
</tr>
<tr>
<td>Imbalance</td>
<td>0.61</td>
<td>0.43</td>
<td>1</td>
</tr>
<tr>
<td>AEP</td>
<td>-0.83</td>
<td>-0.12*</td>
<td>-0.65</td>
</tr>
</tbody>
</table>

Table 5-11 Linear correlation coefficients (p<0.01 except*)

It would be expected that when over-deliveries occur they do so because adjacent sectors are saturated and demand cannot be met. In fact, over-deliveries and imbalance are highly correlated (0.61) meaning that over-deliveries occur precisely when sectors are incorrectly balanced. This suggests that an incorrect sector traffic balance may be a fundamental source of traffic over-deliveries.
This finding supports the need to implement airspace balancing measures as proposed by the SESAR programme (e.g. dDCB concept (SESAR, 2012)) in order to make more efficient use of the airspace, thereby relieving traffic congestion and reducing safety risks.

### 5.3.3 MUAC OCE

The mean OPE value during the analysis period is 0.82 and the utilisation is 0.58. The OCE for the analysis period is stable (standard deviation of 0.04) with a mean value of 0.48. This value corresponds to 48% of the potential ATCO workforce allocated during the first stage of the planning process being used to its full extent.

![Figure 5-13 OCE and its two functional metrics](image)

**Figure 5-13 OCE and its two functional metrics**

### 5.3.4 MUAC case study conclusions

This section has investigated the accuracy of the MUAC planning process, its historical evolution, the performance of the ASM function and the overall cost-efficiency of the ACC (OCE metric).

The analysis has shown that the OCE of the centre is 48% and that this value is degraded fundamentally by a low utilisation of airspace sectors. The utilisation of the airspace can be enhanced by an increased air traffic demand and by a more accurate selection of the airspace configuration. While the air traffic demand cannot be adjusted from an ACC perspective
(there are methods such as more attractive route charges for airlines although this is not considered within this research), there are means to select more accurate airspace configurations. This however relies on accurate predictions during the timeframe when airspace configurations are tactically chosen (60 to 20 minutes prior to execution).

The analysis has unveiled the importance of the overstaffing on this metric in the accuracy of the planning process (OPE metric). It has shown the enhanced performance of the planning process following the implementation of new tools and procedures. Future enhancements to the OPE are not seen as feasible unless a revision of the ATCOs’ contractual agreements is undertaken. Although assessing this revision is not the aim of this thesis, it has to be noted that it would convey very delicate socio-political aspects and therefore no major changes should be expected at least in the short or medium future.

The planning process was shown to be evolutionary although no major refinements are accomplished until the 3rd stage. This suggests that the available information during the 1st and 2nd planning stages is not sufficiently accurate to undertake major changes to the plan. However, no conclusions could be drawn on the capacity/cost-efficiency trade-off, fundamentally due to the lack of staffing-induced delays. As a result a further case study was carried out to attempt to address this issue.

5.4 GUAC Case Study

In this section, the methodology developed in Section 5.2 is applied to GUAC. This case study therefore enables to carry out a comparative analysis between two different planning processes.

5.4.1 Planning process accuracy assessment

The GUAC planning process is comprised of the following stages:

- 1st stage:

The result of the 1st stage of the planning process is the identification of the number of ATCOs needed, i.e. the ORT. These resource requirements are published each year in August
and contain the ATCOs’ needs for each day for the entire next year (January to December). Therefore, the LAT of the 1st stage of the planning process is variable, e.g. five months for January and sixteen for December.

This variability in the LAT indicates that for GUAC the LAT is not perceived as a relevant factor affecting the planning process accuracy when it is larger than 5 months [5-22]. This finding was further validated by the ACC staff planner at GUAC. In other words, the information available at this stage is not considered sufficiently reliable. Therefore until two months before the actual day of operations, when the next planning stage occurs, the amount of planning accuracy that can be gained with reduced LATs is not considered significant enough.

\[ Planning\ Accuracy \neq f\ (LAT) \text{ for } LAT > 5\ months \]

The resulting plan generates baselines of ORTs for each month in the year. This approach allocates all days in a given month the same number of ATCOs. It is therefore by definition not capturing daily traffic variations, thus requiring additional buffers. An exception occurs when the existence of additional or fewer resources demand is accurately known, such as on January 1st, when worldwide traffic is significantly lower and the baseline is accordingly modified.

• 2nd stage

The 2nd stage begins two months before the start of the month in question and ends one month later with the publication of the final roster.

During this stage, ATCOs are allocated specific shifts and short-term information is incorporated into the plan in the event of significant variations e.g. industrial action. In reality the short-term information is incorporated as it becomes available, therefore it can potentially be included in the plan before the start of the 2nd stage. However, since there is no record on when this update is produced, it is associated with the 2nd stage.

The variation with respect to the baseline plan published at the end of the 1st stage is very low and, excluding special events, it is usual to maintain the monthly-baseline for each day. This
approach is not able to capture the daily and seasonal trends discussed in Section 3.3.2, and therefore the ATCO needs. This will have a negative effect on the cost-efficiency as discussed in Section 5.4.2.

Similarly to the MUAC, during the day of operations, ATCOs are managed according to short-term predictions of air traffic demand (LATs of up to two hours). This staff management is carried out through the ASM function and depends fundamentally on the working procedures and habits of the operation room supervisor and the accuracy of the short-term traffic predictions.

5.4.2 OPE and delay relationship

Data analysed for the GUAC case study covers the period from 18-Dec-2009 (when the current 6-sector configuration for the upper airspace was implemented) to 31st December 2013. Only one day was excluded from the data set due to incorrect data recording.

The delay per source type for Skyguide GUAC is shown in Figure 5-14. Although GUAC differentiates between staffing- and sickness-induced delays, this analysis groups both delay types into the same category: staffing. In fact, for the purposes of the analysis the above distinction is irrelevant. Sickness is an unforeseen event which should be accounted for in the buffers of the planning process and therefore should not be analysed as a separate factor.
Staffing delays account for 40.3% of the total ATFCM delays in the GUAC. This category has the largest share across all delay types, hence a correlation is expected between the shortage of ATCO staff, the planning accuracy and the capacity shortages (delays), contrary to the results from the MUAC case study where no such delays were found.

In order to determine this potential relationship a distinction is made between days on which staffing delays occurred (staffing delays > 0 minutes) and days on which staffing delays did not occur (staffing delays = 0 minutes). For each day in both of the two staffing delays groups, the OPE is calculated according to [5-8]. Figure 5-15 shows the frequency histogram for both distributions.
Figure 5-15 shows different distributions for zero and non-zero staffing delays for different OPE values. Visual inspection of this figure indicates that larger cost-efficiency values are seen for days when staffing delays occur. This result reveals that a more accurate plan (large OPE) is more likely to lead to staffing shortages (reduced capacity), i.e. existence of a capacity cost-efficiency trade-off.

Nevertheless, no relationship between the magnitude of the delay and the OPE was established (see Figure 5-16). This absence of relationship is likely due to the qualitative implementation of the delay measures (e.g. low, medium and high delays), not accounting for the actual severity of the capacity shortage.

In fact, the analysis of all the staffing-related regulations in the 3-year period of study shows that the applied regulations tend to be very similar, with similar delay magnitudes. During the analysis period, only 10 different staffing-related regulations were applied: 0, 107, 387, 494, 696, 711, 1083, 1190, 1611, 1670, and 1777 minutes (Figure 5-16). This suggests that FMPs apply regulations using fixed values (qualitative measures). This prevents establishing a more accurate relationship between the OPE and staffing delays.
An alternative approach is used to quantify this relationship. This approach focuses on measuring the relationship between OPE and the existence of delay as opposed to OPE and the magnitude of the delay: it computes the probability of finding a staffing delay (regardless of its magnitude) in the analysis period for the different OPE values.

To this aim, OPE is segmented in 100 different intervals from OPE=0 to OPE=1. The probability of obtaining a staffing delay within each of the OPE intervals is subsequently calculated through [5-23]:

\[
 p_{\text{OPE interval \ staff delay}} = \frac{\text{frequency delay days}}{\text{frequency delay days} + \text{frequency no delay days}}
\]  

[5-23]

The OPE and the probability of the staffing delay as a function of OPE is plotted in Figure 5-17. This figure shows that OPE tends to concentrate around its mean (\(\mu_{\text{OPE}} = 0.493; \sigma_{\text{OPE}} =0.059\)). This implies that for the regions falling outside the mean, the staffing delay probability is highly dependent on a few days sample, which may bias the results, i.e. if there is only one day with OPE=0.3 and this day has a staffing delay, the analysis would yield a probability of 1 for OPE=0.3, based only in one day.
Figure 5-17 Density plot for GUAC OPE

In order to address this issue, only data within a 1-standard deviation value from the mean are taken into consideration: $OPE = [0.434,0.552)$. This area corresponds to the region between the two red dashed-lines in Figure 5-17.

Figure 5-18 zooms in on the study interval ($OPE = [0.434,0.552)$) with the green points representing the observed probability of obtaining staffing delays as a function of the OPE. Figure 5-18 indicates a trend in which the probability increases as the OPE rises. This confirms the hypothesis that OPE (planning cost-efficiency) and staffing delays are positively correlated.
Finally, the observed probability of obtaining staffing delays is empirically fitted by a power functional relationship in the form of [5-24]:

\[ P(OPE) = a \times OPE^b + c \]  

Where “\( P \)” is the probability of observing staffing delays and “\( a \)”, “\( b \)”, “\( c \)” are the parameters computed through a means square method (R-square: 0.9145).

Table 5-12 Fit parameters of the probability functional relationship

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>5368.0130</td>
</tr>
<tr>
<td>b</td>
<td>20.7700</td>
</tr>
<tr>
<td>c</td>
<td>0.01385</td>
</tr>
</tbody>
</table>

The results show that staffing delays, and subsequently the capacity shortages are directly proportional to the OPE. This means that as the accuracy of the planning process increases (OPE), so does the capacity shortages: this relationship constitutes an indicator of the capacity / cost-efficiency trade-off.

Ideally the analysis, should aim to find the relationship of delay to OCE, instead of OPE, since at discussed in Section 5.2.3, the former is a more reliable metric for cost-efficiency.
The OCE is the result of multiplying OPE by the utilisation. Historical utilisation data was not available at GUAC and therefore, OPE was used as an indicator to evaluate the cost-efficiency buffer. This limitation of the analysis is included as a future work to enhance the framework area in Section 11.3.

Furthermore, the computed trade-off relates a cost-efficiency indicator with a capacity shortage metric i.e. delay. Although delay is used as an airspace capacity metric, specially for network performance monitoring (e.g. (FABEC, 2012)), delay is a measure of insufficient capacity rather than a measure of available capacity. Therefore, delay is not the optimal metric for quantifying the cost-efficiency buffer (Figure 5-1).

5.4.3 Quantification of the cost-efficiency buffer

In order to translate the delay proxy into an occupancy cost-efficiency buffer, there is a need to translate delay into an occupancy value. In order to accomplish this objective the 2-step process below is proposed:

1. Calculate instantaneous available capacity shortages (measured as occupancy). The excess of traffic demand over the available capacity at each instant when an ATFCM delay measure is cleared constitutes the instantaneous cost-efficiency buffer:

   \[ C - E\ buffer = predicted\ occupancy - available\ capacity \]  

   Being this equation applicable only if the result is greater than 0.

2. Computation of the traffic excess over a representative sample (e.g. summer period) and inference of the relationship to delay.

In order to perform this 2-step process the following data set is needed:

- Daily evolution of ATFCM en-route staffing delays. This data should be obtained from the NM en-route ATFCM staffing delays for the GUAC airspace;
- Daily evolution of occupancy predictions for GUAC airspace. This data should be retrieved from the ETFMS system of the NM; and
- Daily evolution of the available configuration. This data should be retrieved from
internal systems at the GUAC.

This analysis is not accomplished in this thesis as the air traffic demand could not be computed due to data unavailability. Therefore the methodology developed in this chapter is limited to establishing the link between cost-efficiency and delay, being delay a proxy of airspace capacity shortages.

Section 11.3 incorporates this methodology limitation as part of the future work identified to enhance the research developed in this thesis.

5.5 Discussion of Results

On the basis of the MUAC and GUAC case studies, this section compares the performance of the planning process in each of the two ACCs. In addition, it discusses the effects of some SESAR OIs on the airspace capacity and cost-efficiency in the light of the findings in this chapter.

5.5.1 Comparison of MUAC and GUAC planning processes

Sections 5.3 and 5.4 have quantified the accuracy of evolutionary (MUAC case study) and rigid (GUAC case study) planning processes respectively. The current section compares the relative performance of the accuracy of both planning processes for the period between 18 December 2009 and 30 September 2012.

Figure 5-19 shows the relative performance of the OPE metric for MUAC and GUAC. The MUAC OPE steadily outperforms GUAC OPE. This difference is more significant during the summer than during the winter season.
Average OPE values for the winter season (from October to March) and for the summer season (April to September) are shown in Table 5-13.

Table 5-13 Comparison of summer and winter OPE average values

<table>
<thead>
<tr>
<th></th>
<th>( \mu_{\text{OPE}} )</th>
<th>MUAC</th>
<th>GUAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>0.81</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>0.70</td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

As discussed in Section 5.2.1.8, the OPE metric is a function of the overstaffing magnitude and the accuracy of the traffic estimations. During the summer, when overstaffing is not significant and the \( \Delta_{\text{ORT}} \) metric is therefore close to 1, the OPE value is fundamentally driven by the accuracy of the estimation of the air traffic demand.

In these conditions, the MUAC OPE is 18 points above the GUAC OPE. The lower OPE for GUAC can be attributed to the inaccuracy of the predictions. This is likely due to the execution of the GUAC planning process. The initial plan (yearly plan developed in August) is not adjusted until one month prior to execution and is based on common SOT baselines, which do not capture the seasonal and daily variations of traffic, leading to lower OPE and
higher cost-inefficiencies.

5.5.2 The role of the SESAR programme

Based on the findings in this chapter and given the SESAR OISs expected to be deployed according to the SESAR Master Plan (SESAR, 2012), this section discusses the feasibility of these OIs in producing any significant benefit to the current ATM system. A discussion of the impacts of the findings of this chapter in the expected performance of the SESAR OISs is achieved.

- Flexible Sectorisation Management

Table 5-14 – SESAR OI step definition (SESAR, 2014). * Operational Focus Area (OFA); Initial Operating Capability (IOC); Full Operating Capability (FOC)

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OFA*</th>
<th>IOC*</th>
<th>FOC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOM-0801</td>
<td>Dynamic sectorisation and constraint management</td>
<td>31-12-2010</td>
<td>31-12-2016</td>
</tr>
</tbody>
</table>

The aim of this OIS is to make more efficient use of the resources (ATCOs) through enhanced ACC planning procedures and rosters. Section 5.2.1 has analysed the effects of refining the planning process, introducing a flexible roster and deploying tools to dynamically manage the staff at MUAC. The results show that overstaffing masks the enhancements achieved by these modernisation initiatives. Improved contractual agreements rather than enhanced technical capabilities are needed to produce any significant cost-efficiency benefit in the future.

With the revision of the contractual agreements, a potential 0.2 and 0.3 increase in summer and winter respectively can be achieved in the OPE metric (Table 5-8).

- Interactive Network Capacity Planning and Co-ordinated Network Management
  Operation Extended until the Day of Operation

Two OISs are mapped under the same category due to the similarity of their objectives.
Both OISs promote sharing with the relevant stakeholders any significant variation in the airspace performance (e.g. capacity shortfall due to equipment maintenance). This sharing of information is achieved whenever the information becomes available, from long-term to short-term in order to accommodate ad-hoc plans. This variation to the plan is captured by the PRR metric.

These OIs allow to better manage the staff (break allocation) to accommodate the demand resulting from unforeseen events and therefore avoid capacity shortages. In addition, it supports the traffic balance of the airspace sectors, by transferring traffic from the saturated to the unloaded sectors. As shown in Table 5-10, an average utilisation of airspace sectors of 60% suggests that the balance of air traffic across sectors is feasible and can produce a more robust and cost-efficient air traffic network.

- The Business Trajectory

The business trajectory concept is the European implementation of the TBOs. The military version of the civil business trajectory is the mission trajectory. The mission trajectory shares the same principles with the business trajectory.

In the European TBO concept implementation, the business trajectory is an evolutionary entity. The initial Business Development Trajectory (BDT) with airspace user preferences is made available to relevant stakeholders through the Shared Business Trajectory (SBT) and finally results in an agreed trajectory, the Reference Business Trajectory (RBT).

The business trajectory concept is expected to be implemented through successive OISs (Table 5-16).
Table 5-16 – SESAR OI steps definitions associated with the business trajectory concept (SESAR, 2014)

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OFA</th>
<th>IOC</th>
<th>FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUO-0203-A,B,C</td>
<td>Business and mission trajectory</td>
<td>2016</td>
<td>2025</td>
</tr>
<tr>
<td>AUO-0204-A,B,C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The development of accurate trajectories as opposed to simple flight plans will theoretically increase the quality of the air traffic predictions. Enhanced predictability should theoretically enable improvements in the staff allocation for long-term, although it has been seen that not this factor but the overstaffing is currently limiting the cost-efficiency performance. The business trajectory concept will have a more significant impact on other ATC domains such as short-term predictability (CHAPTER 6 and CHAPTER 7).

- Generic (non-geographical) Controller Validations

Table 5-17 – SESAR OI step definition (SESAR, 2014)

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OFA</th>
<th>IOC</th>
<th>FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDM-0203</td>
<td>Sector teams operations</td>
<td>31-12-2015</td>
<td>31-12-2018</td>
</tr>
</tbody>
</table>

Staffing shortages have been shown to be a major source of cost-inefficiency (e.g. 40.3% of total delay in GUAC). With the introduction of ATCO licenses for multiple airspaces, more staffing options under constraining scenarios may become available. However, in order to guarantee safety, generic ATC licenses are unlikely to happen until more automation becomes available and operations are less dependent on specific airspace procedures.

- Enhanced Real-Time Civil Military Coordination of Airspace Utilization

Table 5-18 – SESAR OI step definition (SESAR, 2014)

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OFA</th>
<th>IOC</th>
<th>FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOM-0202</td>
<td>Airspace management</td>
<td>31-12-2012</td>
<td>01-01-2015</td>
</tr>
</tbody>
</table>

This OIS emphasises again the need to dynamically share information. In this case, the information shared is concerned with the use of reserved airspace volumes by the military.
stakeholder. An increased coordination between military ATSUs and civil ANSPs can produce a more cost-efficient use of the airspace avoiding under-utilisation. Tools like the Local and Regional ASM Application (LARA) are currently being deployed to support this OIS.

In Section 5.3.2 the effects of the presence of military activity on the performance of the ASM function were discussed. A comparative analysis of weekends (no military activity) vs. week-days (military activity) was carried out on the basis of the APE metric. This metric is used instead of the OPE since the results of the latter include factors other than the military activity (e.g. staffing factors), which could bias the results.

A t-test for the weekends and week-days APE distributions fails to reject the null hypothesis that both distributions come from the same population at a 95% confidence level (p≈0). Therefore, no significant effect in the planning process accuracy is seen due to the military effect. This finding suggests that increased civil-military coordination can have a positive impact on the ASM function performance with higher utilisations, although the planning process is not expected to suffer major changes.

- Sector Team Operations Adapted to New Roles for Tactical and Planning Controllers

Table 5-19 – SESAR OI step definition (SESAR, 2014)

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OFA</th>
<th>IOC</th>
<th>FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM-0301</td>
<td>Sector Team Operations</td>
<td>31-12-2014</td>
<td>31-12-2017</td>
</tr>
</tbody>
</table>

New roles are envisioned within the SESAR operational concept although their definitions are still immature and not likely to be implemented in the foreseen timeframes. Research, e.g. (Tien and Hoffman, 2009), has been carried out to quantify the benefits (in capacity and cost-efficiency terms) of introducing new roles such as the Multi-Sector Planner (MSP).

The MSP is envisioned to act as a PC in two operational sectors simultaneously. This would reduce the ATCO workforce as well as the capacities of the affected sectors. When air traffic demand is not significant, this new role would support the implementation of a solution which offers a lower capacity tailored to the needs and with a reduced workforce: for 2
sectors, 3 ATCOs instead of 2. The cost-efficiency gains would therefore be apparent.

5.6 Summary

This chapter has introduced a methodology to assess the cost-efficiency of ACC operations. The operational cost-efficiency and airspace capacity were found to be closely related since the latter can be achieved by a degraded performance of the former.

The operating cost-efficiency of the ACC was found to be driven by the accuracy of the planning process and the execution performance of the ASM function. A methodology was developed to assess each of these independently as well as the overall resulting cost-efficiency, in other words the OCE metric.

The application of the methodology for the assessment of the planning process accuracy in the MUAC has determined that overstaffing is the most cost-inefficient factor. A revision of ATCOs’ contractual agreements has been proposed as a way to increase cost-efficiency by means of providing a more dynamic workforce.

A comparison of the planning process for the MUAC (strategic layered planning process) and GUAC (rigid planning process) was carried out. The strategic planning process has shown enhanced performance, more significantly during summer periods. This suggests the need to implement a refined planning process in European ACCs in order to augment cost-efficiency without comprising the available capacity.

The research has found that the cost-efficiency is also a function of the ASM execution performance. A correct use of the available resources through an accurate selection of the airspace configuration is needed to achieve high cost-efficiencies. For the MUAC case study it was found that the utilisation of the airspace is close to 60%, indicating that the selection of the airspace configuration to meet the air traffic demand is still a major source of inefficiencies.

An assessment of the achievement of the ASM objectives has been carried out to avoid biasing the cost-efficiency results. The analysis has shown that utilisation and over-deliveries are correlated, therefore indicating that the optimum utilisation values (utilisation close to
airspace capacity) are also indicators of less safe ACC operations. This constrains the application of potential cost-efficiency improvements through more intense use of the airspace.

An attempt to quantify the cost-efficiency buffer was made for the GUAC case study, however data were unavailable. To provide with an indicator of the buffer, the trade-off between planning accuracy and delays was investigated. A power functional relationship between staffing delays and OPE was established. This result suggests that the more accurate the planning process is, the more likely the ACC will be to encounter capacity shortages during operations. This is explained by the ACC being less flexible to temporarily increase available capacity to meet unexpected air traffic requirements.

Finally a qualitative discussion of the OISs proposed by SESAR with potential effects on cost-efficiency was carried out, based on the findings from the application of the developed methodology to the two case studies. The potential benefits of these OISs are limited by ATCOs’ contractual agreements and seasonal traffic periods (leading to overstaffing), although the introduction of new sector team roles and increased situational awareness between relevant stakeholders is seen as a major contributor for future enhanced ATM performance.
CHAPTER 6  DEVELOPMENT OF A PREDICTABILITY ESTIMATION FRAMEWORK

The objective of this chapter is to develop the predictability (ASM/ATFCM) framework area.

Figure 6-1 Airspace capacity estimation framework (focus of this chapter highlighted in blue)

Accurate predictability is a key enabler of the strategic optimisation of the ATM system performance. It is fundamental across the whole range of ATM stakeholders over varying time frames.

In the SESAR concept of operations, accurate air traffic predictions are the cornerstone of the TBOs concept (SESAR, 2007a). Accurate predictions enable amongst others to improve the quality of the information distributed to the stakeholders in order to increase the situational awareness of the future state of the system (SESAR, 2008c).

In the previous chapter the importance of accurately predicting air traffic demand over strategic time-frames was discussed in order to enable accurate advance workforce planning. Similarly, predictability is crucial over pre-tactical, tactical and execution time-frames. For instance, AOCs manage their ground assets based on the predicted time of arrivals of the flights over the pre-tactical and tactical time-frames; ATFCM predicts the traffic complexity...
and demand to ensure a balanced demand/capacity airspace over the pre-tactical time-frame; on-board aircraft equipment predicts the aircraft trajectory to operate the aircraft according to the cleared route; and ATC predicts flight trajectories to ensure maintaining separation minima of flights within acceptable workload levels during the execution time-frame (Loft et al., 2007).

In this chapter and CHAPTER 7, a framework is developed for the assessment of pre-tactical air traffic predictions, which as discussed in CHAPTER 4, affect airspace capacity. These predictions are produced by the NM and are used by ANSPs to develop the ASM/ATFCM functions.

The framework assesses the accuracy of the predictions made by the NM in two separate domains: the temporal accuracy of flight trajectory predictions and airspace sector occupancy predictions.

The inaccuracy of occupancy predictions relates to the amount of airspace capacity wasted due to safety buffers, whilst the temporal prediction inaccuracy will prove the effectiveness of the individual flights ATFCM measures to enhance airspace capacity.

Section 6.1 introduces the concepts of air traffic predictability. Section 6.2 analyses the effects of the lack of predictability on the ACC performance and specifically the airspace capacity. This is followed by a discussion of the air traffic prediction system in Europe in Section 6.3. The results of the analysis motivate the development of a predictability estimation framework in Section 6.4. In this section a general overview of the framework is provided, followed by a detailed analysis of each of the framework modules. A set of programming tools is developed to support the framework implementation at different ACCs. Finally, Section 6.5 describes these functions and the relationships between them.

### 6.1 Air Traffic Predictability and Uncertainty

The predictability of air traffic is a function of two key parameters:

- The accuracy of the prediction i.e. the error associated with the prediction (Morton et al., 2010).
• The LAT or time horizon associated with the prediction i.e. the time difference between the prediction of an event and the actual occurrence of that event (Schuster and Ochieng, 2011).

The accuracy of the prediction is driven by the following factors:

• Complicatedness

The ATM system is a complex system, with many interactions between stakeholders, which can be difficult to model (e.g. human factors). Atmospheric conditions (wind, temperature, pressure, storm locations) change rapidly and are a fundamental source of uncertainty (Tysen et al., 2002) as well as aircraft performance (Dougui et al., 2012).

Finally, the errors associated with the nominal prediction model, due to the assumptions made and their uncertainties constitute another source of predictability inaccuracy (Jackson et al., 1999, W., 2015).

• Criticality

The ATM system can be very sensitive to small changes. For instance, a relatively small drop in temperature can result in snow accumulating on the surface of runways, potentially requiring an interruption to operations.

• Distributed and adaptive decision making

The ATM system is formed of many stakeholders, each of whom has a focus on optimising their own operations, each using their individual business model. A further difficulty is associated with predicting the future intent of the system components. For instance, a given trajectory can be dynamically amended by ATC to address potential conflicts.

• “Shaky-hand” effects

These are the result of non-compliance with existing agreements between different stakeholders (e.g. variations between the Calculated Take-Off Time (CTOT) and the Actual Take-Off Time (ATOT). Additionally, the aircraft may not follow the agreed trajectory due to variations in aircraft performance.
• Catastrophic events

This includes any non-predictable event external to the nominal operations, e.g. volcanic ash.

A key prerequisite to the development of a predictability framework is the determination of the predictability requirements (Morton et al., 2010, Schuster and Ochieng, 2011). Various approaches have been taken: some studies develop metrics to measure average predictability levels for specified LAT intervals (Ball et al., 2000), whilst others look at predictability as a continuous function of the LAT (Cdsek et al., 2007).

The characterisation of the flight Trajectory Prediction (TP) errors is carried out in the following dimensions: the temporal dimension and the three components for the spatial dimension (Schuster et al., 2012). The TP error is computed as the difference between the predicted trajectory and the executed trajectory (Paglione et al., 1999).

The spatial errors are calculated as the 3-dimensional geometric errors. For the temporal dimension, time errors are calculated for characteristic trajectory points, which are significant points along the trajectory from an operational perspective. These include:

• the TOT
• ACC Entry/Exit Times (ETI/XTI)
• Airspace Sector ETI/XTI

All errors evolve as a function of the LAT. From an ASM/ATFCM perspective the temporal dimension is the most relevant, as shown in the next section, although few studies have been accomplished in this area (e.g. (Fernández and Cordero, 2013, W., 2015)). Therefore, this chapter takes this last approach.

### 6.2 Prediction Accuracy and Airspace Capacity Relationship

The TP process consists in predicting the future position of a flight based on its current position, the aircraft intent and the aircraft performance, given certain environmental and airspace conditions (Tysen et al., 2002, Mondoloni and Swierstra, 2005).
The TP accuracy is extremely relevant to ATCO workload, and therefore airspace capacity, since it affects the situational awareness of the ATCO and the knowledge on the aircraft intent. For instance, (Cano et al., 2007) discusses the importance of accurately predicting ATCO workload to strategically adapt the airspace configuration.

The prediction of the aggregated air traffic density across airspace sectors, referred to in this thesis as air traffic prediction, affects the airspace capacity through the performance of the ASM/ATFCM functions. For instance, studies such as (EUROCONTROL, 2009) highlight the importance of improved flight plan adherence to reduce the occurrence of ATCO overloads. However, the impacts of the lack of predictability on the ATM system performance and specifically on airspace capacity remain unclear.

Accurate air traffic predictions are crucial for the development of the ASM/ATFCM functions to prevent traffic over-deliveries. Although traffic over-deliveries do not necessarily result in ATCO overloads, for the vast majority, over-delivery is a necessary condition. Additionally, in order to maintain the cost-efficiency of the operations, FMPs will ensure that the available capacity accurately matches the demand, without being excessive (CHAPTER 5).

Discussions were conducted with FMPs from the MUAC and GUAC to assess the impact of the lack of predictability on the development of the ASM/ATFCM functions. The objective of the discussions was to assess the perception of FMPs on the following:

- The impact of predictability accuracy on airspace capacity.
- The impact of enhanced predictability on the performance of ASM/ATFCM operations.

FMPs were aware of the inaccuracies of the air traffic predictions and agreed that the lack of predictability lead them to be more conservative in the decisions made during ASM/ATFCM operations. In addition, they acknowledged that this conservative performance is translated into a sub-optimal performance of the ASM/ATFCM functions, in order to ensure that safety is maintained throughout the operations.

The ASM/ATFCM functions rely on air traffic predictions, which are carried out prior arrival in the airspace sectors, in order to allow a strategic management of the airspace. Traffic
demand assessments are typically carried out between 4 hours and 20 minutes before the arrival of the traffic, i.e. the pre-tactical time-frame. During this time-frame, predictions in Europe are made by the NM. These predictions are presented to the FMPs of the different European ATC centres through the Central flow management unit Human-Machine Interface (CHMI) tool. However, these predictions are less accurate than those from on-board aircraft or by the AOC (Tysen et al., 2002).

When air traffic predictions indicate that the demand of an airspace sector will exceed its capacity limits, FMPs assess the feasibility of implementing one of the following solutions (Cook, 2007):

- Change of airspace configuration (ASM function).
- Traffic re-routing (ATFCM function).
- Level capping (ATFCM function).
- Regulation (ATFCM function).

When the demand is low and operations are cost-inefficient, FMPs select a more adequate airspace configuration (ASM function).

In capacity terms, the uncertainty of the predictions becomes increasingly relevant when demand approaches the sector capacity. The ASM and ATFCM functions make use of the Traffic Monitoring Values (TMVs) to monitor if demand is near capacity.

The TMV value represents the level of air traffic demand that each airspace sector can safely accept. This capacity corresponds to the sector capacity reduced by the predictability buffer i.e. the declared capacity. The predictability buffers are set by the ASM and ATFCM functions based on the inaccuracy of the air traffic predictions and their effect on the ATCO function. Nevertheless, these buffers are established based on FMPs acquired experienced and are not quantified through a formal method.

In order to estimate the magnitude of these buffers and the effects that prediction accuracy have on the airspace operations performance, a framework is developed in subsequent sections of this chapter. The section below introduces the European automated system used by the NM to carry out the predictions for the ASM and ATFCM functions.
6.3 The Enhanced Tactical Flow Management System

The ASM and ATFCM functions in Europe are assisted by the Enhanced Tactical Flow Management System (ETFMS), which has been developed and is maintained by the Eurocontrol NM. ACCs are equipped with a remote ETFMS tool that displays air traffic predictions in their area of influence. One of the main data sources for the development of this framework is ETFMS data, hence an adequate understanding of this system is deemed necessary.

The ETFMS receives information from two main sources:

- Air traffic intent (fundamentally flight plans).
- Position reports (e.g. radar surveillance).

This information is shared with the relevant stakeholders: airspace users, ACCs, airports and the NM. ACCs and airports are equipped with Entry Nodes, which automatically update, and communicate to the ETFMS, the information of the flights under their responsibility. Airspace users communicate their intent through the flight plan submission process. This communication process is achieved through a set of pre-defined messages which can automatically be sent and processed by all the actors involved in the process. Table 6-1 lists the types of messages received by the ETFMS:
Table 6-1 ETFMS flight progress messages

<table>
<thead>
<tr>
<th>Input to ETFMS</th>
<th>Output of ETFMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Name</strong></td>
<td><strong>Name</strong></td>
</tr>
<tr>
<td>IFP</td>
<td>EFD message</td>
</tr>
<tr>
<td>Initial Flight Plan message</td>
<td>ETFMS Flight Data message</td>
</tr>
<tr>
<td>APR</td>
<td>FUM</td>
</tr>
<tr>
<td>Aircraft operator Position Report message</td>
<td>Flight Update Message</td>
</tr>
<tr>
<td>DPI</td>
<td></td>
</tr>
<tr>
<td>Departure Planning Information message</td>
<td></td>
</tr>
<tr>
<td>FSA</td>
<td></td>
</tr>
<tr>
<td>First System Activation message</td>
<td></td>
</tr>
<tr>
<td>CPR</td>
<td></td>
</tr>
<tr>
<td>Correlated Position Report message</td>
<td></td>
</tr>
</tbody>
</table>

The IFP message contains information on the flight plan prepared by the AOC hours before the actual start of the flight. The APR message is sent by airspace users flying long-haul routes before entering the ETFMS coverage area. The DPI message is sent by airport operators and includes updated information on the predicted TOT of the flight. The FSA message is sent by the ACCs upon arrival of the flights in their airspace. The CPR message is sent every minute from the ACCs to the ETFMs and contains the latest individual flight positioning report.

The data is processed by the ETFMS and merged with environmental data (weather and network situation) resulting in the ETFMS Flight Data (EFD), which is used for two
purposes: the Computer Assisted Slot Allocation (CASA) process and traffic and demand predictions.

CASA assigns airport departure slots. The CASA process identifies flights that may cause demand/capacity imbalances and creates individual regulations. These regulations are implemented through the allocation of a CTOT, which the flight is required to follow.

Traffic and demand predictions computed by the ETFMS, are shared with relevant stakeholders, including ACCs, using EFD and FUM messages (Table 6-1).

The EFD message contains short-term information on the actual and predicted trajectories of flights. The FUM is similar to the EFD message, although it is sent to stakeholders that are not expecting the flight in their airspace.

Since EFD messages contain all the information incorporated by the other messages, EFD will be the focus of the framework developed in the next section. An example of such message is shown in Appendix 5.

In general, the messages can be grouped into messages associated with the time-period prior to the TOT and those with the time-period post TOT. The former are sent by the airport operators, airspace users (e.g. airlines) and the NM, updating the flight plan. The latter are sent by ATC centres and contain information on actual aircraft positions.

Therefore before a flight is airborne, the ETFMS predictions are fundamentally based on the flight plan submitted by the aircraft operator and on the constraints imposed by airport operators and the NM in case of regulations. Once a flight is airborne, predictions are based on actual aircraft position reports and on aircraft intent. The most common pre-TOT messages are the IFP messages, whilst the most frequent post-TOT messages are the CPR messages.

On the basis of these messages, the ETFMS generates new trajectory predictions, which are shared through EFD messages with relevant stakeholders. These will use the latest predictions to carry out the ASM/ATFCM functions.
6.4 Predictability Framework Development

The objective of the framework is to develop a set of methodologies and supporting software tools to:

- Characterise the temporal error of the trajectories predicted by the NM, which are used to perform the ASM and ATFCM functions.
- Characterise the error of the sector occupancies predicted by the NM based on the predicted trajectories.
- Estimate the existing and the required airspace capacity predictability buffers.

The framework is developed with a focus on implementation across different ACCs in Europe. Currently, NMs and ANSPs across Europe lack a means to characterise pre-tactical air traffic predictability. This framework aims to bridge this gap.

The proposed framework is developed with a modular architecture. Each module has a concrete and independent functionality, which the framework user can choose to use depending on the purpose of each concrete analysis. Each of the modules can be fitted within one of the following framework functional categories (Figure 6-2):

- Data generation
- Error calculation
- Hypothetical new concept testing
As shown in Figure 6-2, there are two modules for each functional category. These are discussed in the following sections below.

6.4.1 Data generation

In order to characterise the pre-tactical air traffic predictability it is necessary to compare the predictions of the air traffic with the actual execution of the air traffic. Data for this comparison are from two sources:

- Track data
- EFD

The two sub-sections below describe each of the data sources.

6.4.1.1 Track data

Track data were the most reliable source of actual flight position available during the development of this framework and are therefore considered as actual flight data. Track data are derived from the ATM Surveillance Tracker and Server System (ARTAS) of the ATC centres, which produce the so-called flight track. In practice, the tracks generated by the ARTAS have an error however, for continental regions in Europe the error magnitude is sufficiently small to be neglected for the purposes of the present analysis. For instance, in the core of Europe (Benelux states) the accuracy of the ARTAS is within a 100 meters error.
This position error magnitude is translated into temporal errors of less than 1 second for flights cruising at ground speeds of 900 km/h. This temporal deviation is considered negligible and therefore the radar tracks are assumed to correspond to the “truth”.

The data analysed by the track data generation module contains the fields indicated in the example in Table 6-2.
Table 6-2 ARTAS flight track example

<table>
<thead>
<tr>
<th>FID</th>
<th>CS</th>
<th>ADEP</th>
<th>ADES</th>
<th>Sector</th>
<th>ETI</th>
<th>XTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>3715797</td>
<td>PIA709</td>
<td>OPLA</td>
<td>EGCC</td>
<td>JEHI(^6)</td>
<td>13:49:35</td>
<td>14:05:54</td>
</tr>
</tbody>
</table>

Where:

- **FID** (Flight IDentification): corresponds to the identification given by ETFMS to each flight.
- **CS** (Call Sign): another means for flight identification used by ATCOs to communicate with individual flights.
- **ADEP** (Airport of DEParture)
- **ADES** (Airspot of DEStination)

### 6.4.1.2 The Enhanced Tactical Flow Management System Flight Data

The predicted flight data is contained in the EFD. This is the data generated by the ETFMS and transmitted to the FMPs through the CHMI. The EFD associated with each flight contains all the predictions made by the ETFMS before the flight actually enters the given airspace sector.

The calculation of the error associated with this data is the key objective of this chapter. Table 6-3 shows an example of how the predictions gathered by the EFD are organised. The same flight as in Table 6-2 is used.

\(^5\) HOHI is the abbreviation for Holstein High airspace sector

\(^6\) JEHI is the abbreviation for Jever High airspace sector
### Table 6-3 EFD predictions example

<table>
<thead>
<tr>
<th>$p$Time</th>
<th>Sector-$p$ETI-$p$XTI Sequence</th>
</tr>
</thead>
</table>

Where:

- **pTime** (predictionTime): corresponds to the absolute time when a prediction is made.
- **pETI** and **pXTI** (predicted ETI and predicted XTI): correspond to the predicted times over a characteristic point.

The second column (Sector-$p$ETI-$p$XTI Sequence) contains the pETI and pXTI for each of the airspace sectors predicted to be crossed. Therefore, its length may vary according to the length of the sector sequence.

In order to generate these data sets, raw data from both sources (track data and EFD) need to be initially pre-processed using the following steps:

- **Time processing**: dates and times in the different fields are in different formats, hence needing harmonisation.
- **Sector naming**: basic sectors are called differently in both data sources, hence a unique terminology is needed.
- **Flight correlation**: the same CS or ADEP-ADES pair can be encountered in the same day in the European airspace. Therefore it is checked that each combination of CS, ADEP, ADES and FID is unique for the day of study.
These data are subsequently used in the calculation of the errors associated with the characteristic trajectory points.

6.4.2 Error calculation

This functional frame computes the error of the predictions. This error is calculated using two different magnitudes: temporal errors and occupancy errors.

In the temporal error the focus is on the time error of the predicted times over a characteristic trajectory point (predicted TOT – pTOT, predicted ETI – pETI and predicted XTI - pXTI). As discussed in Section 6.1, the errors are a function of the LAT which is mathematically defined in the case of the error of the ETI as [6-1]:

\[
LAT = ETI - pTime \tag{6-1}
\]

The occupancy error of the airspace sectors is referred to as the occupancy prediction error for the same LAT.

Two dedicated modules calculate each of the errors.

6.4.2.1 Temporal error

This module is built allowing the user to sort and filter the temporal error per specific flows in order to assess individual error patterns. The temporal error is calculated as expressed in [6-2]:

\[
\text{Temporal Error} = pETI - ETI \tag{6-2}
\]

A positive temporal error implies that the prediction expects the flight to arrive later than the actual arrival, whilst a negative temporal error implies that the flight arrives later than predicted i.e. the flight arrives with delay.

This error can be computed for any characteristic trajectory point. Figure 6-4 plots the evolution of the error in the ETI for the first sector of all the air traffic flying through the MUAC airspace on 07 February 2013.
The temporal error is a function of the LAT, which can be calculated up to one day before the entry of the flight (86400 seconds).

The module allows the user to specify the duration of each LAT interval. For instance, calculation of the error for every LAT in 10 minutes intervals. Due to current ASM/ATFCM operations, one-minute intervals are selected as the most appropriate LAT interval partition magnitude.

The temporal error of each flight is calculated for all the LATs up to one day prior to execution. EFD updates do not occur at a constant frequency, thus there is no prediction update associated for many LATs. In these cases the temporal error is assumed to be the latest available temporal error derived from the latest available EFD update. Figure 6-5 depicts the error interpolation process for a single trajectory. In the plot on the left only the original predictions can be seen, whilst the plot on the right shows the error evolution after the latest prediction has been associated to each one-minute LAT.

Figure 6-4 EFD temporal error for all flights on 07/02/13
In some cases several EFD updates can occur within the same one-minute LAT interval. In order to associate each one-minute interval with a unique prediction, the most recent update is chosen.

The module performs an outlier identification and exclusion based on the deviation from the mean, which can be chosen by the user (e.g. 3-standard deviation exclusion rule). The outlier exclusion rule is iteratively used for every one-minute LAT interval. As shown in Figure 6-4, during some LAT periods and for some flights, predictions show especially large errors. The fundamental source of incorrect predictions are inaccurate inputs (Section 6.1). However, it was observed that on occasions, large errors were the result of data management issues, such as the incorrect association aircraft to flight plans or the incorrect activation of flights in the ETFMS.

Since no logical rule could be implemented to automatically identify these data processing errors, the deviation from the mean rule is considered the most appropriate to detect this type of error.

Figure 6-6 shows the temporal error evolution (mean and one standard deviation) after applying a 3-sigma exclusion rule for the flights depicted in Figure 6-4.
Figure 6-6 shows an enhancement of the mean temporal error for LATs close to zero. However, no major conclusion can be drawn from this figure due to the large dispersion of the error. In fact for large LATs (LAT > 180 minutes) the standard deviation of the temporal error is around 15 minutes. This leads to test the hypothesis that the temporal error is potentially formed of several sub-populations of errors.

An analysis of temporal errors for different characteristic sub-populations is performed. A sub-population is defined as a group of flights that have in common a number of drivers that affect their temporal error e.g. all flights departing from an airport that typically has poor on-ground prediction accuracy. These sub-populations are identified through an identification of the potential factors contributing to its temporal error. These factors include (Section 6.1):

- Information used to compute the TP, e.g. radar track updates
- Algorithms and methods in the TP computation e.g. aircraft performance assumptions

Since the algorithms and methods are equally applied by the ETFMS for each flight, this factor was assumed to have a lower impact than the source information on the grouping of flights into sub-population according to their characteristic temporal error. Therefore, the sub-populations were identified on the basis of the data source used by the ETFMS to make the predictions. ETFMS sources can fundamentally be divided into the following groups:
Predictions made with flight plan information are expected to be less accurate than the predictions based on radar track positioning reports. In fact, the flight plans are a summary of the expectations of the airspace user for the flight assuming no significant variations in speed or flight altitude. These do not capture uncertainties such as pushback delays and take-off queue orders and therefore do not necessarily accurately reflect the TOT (Tysen et al., 2002). On the other hand, radar tracks contain actual information on the aircraft position, which is expected to be significantly more reliable (Marceau et al., 2013).

Figure 6-7 sorts the temporal error for flights using flight plans (on-ground flights) as source data (red) and flights using radar tracks (airborne flights) as source data (blue).

As it is expected, the predictability of flights once they are airborne is significantly more accurate than of that of flights still on the ground. The impact on airspace sectors will therefore be variable. For instance, the predictions associated with higher airspace sectors, which contain a larger number of over-flights, are expected to be more accurate than those associated with lower sectors, which contain more departures.
This different error performance is shown in Figure 6-8. The percentage of flights within an absolute error interval is calculated. The performance of the higher airspace of the Brussels East sector (left figure) is different than in the lower airspace of the Brussels East sector.

In fact, the higher airspace shows a gradual increasing prediction accuracy whilst the accuracy of the lower sector remains almost invariable until LAT=40 minutes. This is due to the great proportion of flights that have not yet departed and which have a low reliable prediction.

On the other hand, in the higher airspace volumes it is usual to find larger number of over-flights. Since these flights have been airborne for larger LATs, their predictions are based on track data for longer times and this reflects into a more accurate predictions and into a more accurate airspace volume.

For instance, for a LAT=60 minutes, Table 6-4 shows the proportion of flights within each absolute error interval, showing the larger ratio of flights with an error below a given value for the high sectors.

Table 6-4 Absolute error distribution at LAT=60 mins for Brussels East High and Low sectors

<table>
<thead>
<tr>
<th>LAT=60 mins</th>
<th>Ratio of flights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute error</td>
<td>High sectors</td>
</tr>
<tr>
<td>&lt; 1 min</td>
<td>23 %</td>
</tr>
<tr>
<td>&lt; 2 mins</td>
<td>40 %</td>
</tr>
<tr>
<td>&lt; 4 mins</td>
<td>64 %</td>
</tr>
<tr>
<td>&lt; 6 mins</td>
<td>77 %</td>
</tr>
<tr>
<td>&lt; 8 mins</td>
<td>84 %</td>
</tr>
<tr>
<td>&lt; 10 mins</td>
<td>91 %</td>
</tr>
<tr>
<td>&lt; 12 mins</td>
<td>94 %</td>
</tr>
<tr>
<td>&lt; 14 mins</td>
<td>96 %</td>
</tr>
</tbody>
</table>
6.4.2.2 Occupancy prediction error

The structure of this module is similar to the previous one, where the error can be sorted and filtered for pattern identification. The metric calculated in this case is the occupancy prediction error. The metric is the one-minute instantaneous geometrical occupancy i.e. any flight geometrically inside the airspace sector at any instant within the one-minute period is added to the occupancy count.

Even though actual occupancies are widely calculated at ACC and NM levels, the framework module calculates itself the actual occupancy instead of using already existing values for two main reasons:

- It enables the testing of different occupancy definitions
- Assumptions on occupancies calculations by ACC and NM were not clearly identified and could potentially be different

Figure 6-8 Flights distribution according to the absolute error for Brussels East High (left) and Brussels East Low (right)
Figure 6-9 shows the difference between the instantaneous one-minute occupancies calculated by the framework module and by the NM. While the differences are not large, the results highlight the importance of using the same definition for occupancy throughout the analysis to avoid additional errors due to inaccurate metric selection.

The occupancy prediction error is given by:

$$\text{Error}_{\text{occupancy}} = \text{Predicted}_{\text{occupancy}} - \text{Actual}_{\text{occupancy}}$$

[6-3]

To compute this error, both the actual and predicted occupancies are required.

**Actual occupancy**

The calculation of the actual occupancy is achieved using the actual flown tracks from the track data source. Track data contain information on entry and exit times to basic sectors (ETI and XTI). This information can be used to calculate the occupancy of airspace sectors. The function developed in that section computes in one-minute intervals the presence of a given flight inside or outside the airspace volume specified by the user.

Detailed analyses of track data showed that flights may enter a given airspace sector more than once, depending on their trajectories. This typically occurs when flights fly near and in parallel to the airspace sector boundaries. Although published airways avoid these situations,
flights cleared by an ATCO to fly direct to a point can end up in this type of scenario (Figure 6-10):

Figure 6-10 Trajectory of a flight close to sector boundaries. Red line corresponds to the airway whilst the blue line corresponds to the flown trajectory.

Direct-to-point clearances are given by ATCOs ad hoc due to the dynamic nature of operations, and can result in large prediction errors. However these errors should not be associated with a poor air traffic predictability, but with the dynamic nature of the ATCO working procedures.

In order to avoid attributing additional error to the ETFMS predictions, the following simplification is made: the flight is assumed to remain within an airspace sector from the first entry until the last exit. Nevertheless, this situation is not frequent since flights are rarely cleared to fly near the sector boundaries as this situation contributes to higher workload levels (Majumdar, 2007).

An example of a flight close to sector boundaries is shown in Table 6-5. The flight enters the
Delta High sector (DELHI) twice. This assumption places the flight geometrically inside the sector between 03:58:51 and 04:12:41, although the flight is not in the DELHI sector between 04:01:25 and 04:05:53.

Table 6-5 Example of an actual trajectory close to sector boundaries

<table>
<thead>
<tr>
<th>Basic Sector</th>
<th>ETI</th>
<th>XTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOHI</td>
<td>03:41:45</td>
<td>03:47:35</td>
</tr>
<tr>
<td>JEHI</td>
<td>03:47:35</td>
<td>03:58:51</td>
</tr>
<tr>
<td>DELHI</td>
<td>03:58:51</td>
<td>04:01:25</td>
</tr>
<tr>
<td>MNHI</td>
<td>04:01:25</td>
<td>04:04:56</td>
</tr>
<tr>
<td>RHHI</td>
<td>04:04:56</td>
<td>04:05:53</td>
</tr>
<tr>
<td>DELHI</td>
<td>04:05:53</td>
<td>04:12:41</td>
</tr>
<tr>
<td>NIHI</td>
<td>04:12:41</td>
<td>04:19:19</td>
</tr>
<tr>
<td>NILO</td>
<td>04:19:19</td>
<td>04:22:16</td>
</tr>
</tbody>
</table>

**Predicted occupancy**

The accuracy of the predicted occupancy is key for an effective ASM/ATFCM function performance as it has been seen in CHAPTER 2.

The EFD contains information on the predicted entry and exit times to basic sectors. This information can be used to calculate the predicted occupancy of airspace volumes defined by a group of basic sectors.

The LAT is defined as the time difference between the time of the prediction and the time the flight crosses an airspace volume (Tobaruela et al., 2014a). However, there are cases in which the ETFMS predicts a flight to cross into an airspace sector without that crossing ever occurring. In this case the actual entry time does not exist, nor does the LAT.

In order to avoid not computing the error associated with that prediction due to the non-existence of the LAT time, the LAT is calculated as the time difference between the time of the prediction and the predicted crossing time to the airspace volume as in [6-4]:

\[
LAT_{equivalent} = pETI - pTime
\]  

[6-4]

The predicted occupancy will therefore be for each airspace sector a function of the LAT.
(Figure 6-11), using the one-minute instantaneous occupancy definition.

Figure 6-11 Actual (LAT=0) and predicted occupancy (LAT>0) during a period of the day for different LATs

**Error of the occupancy prediction**

The occupancy prediction error is defined as:

\[
Error_{\text{occupancy}} = \text{Predicted}_{\text{occupancy}} - \text{Actual}_{\text{occupancy}} \tag{6-5}
\]

A positive error implies that a larger than actual number of traffic was predicted, and vice versa.

The tool module developed within the framework has the capability to filter the error contribution according to flows. Figure 6-11 shows this error for every minute for the EGLL departures and the remaining flows.
Figure 6-12 Example of occupancy error (y-axis) as a function of the LAT (x-axis). Snapshot made at 08:32 UTC for EGLL departures (blue) and the rest of the traffic (green).

Figure 6-12 shows that the occupancy error is a function of the LAT and that varies across airspace sectors. An aggregated analysis of occupancy prediction error per airspace sector revealed the existence of a stationary error caused by the incorrect activation of flight plans by the ACCs: although flights are sharing more accurate information than the one reflected in the EFD, the system is unable to recognise it.

For larger LATs, the proportion of flights that have not been activated increases. This has a negative effect on the occupancy prediction, underestimating on average the occupancy. This effect is shown in Figure 6-13.
The trend of the proportion of activated flight plans can be seen to be very similar to the trend of the average mean error, with a strong correlation between the two ($r=0.903$, $p<0.05$).

It is assumed here that the plan activation effect does not have an impact on the standard deviation, i.e. missing flights are equally distributed amongst flights overestimating and underestimating the occupancy.

Due to the numerous factors affecting the accuracy of the predictions and the complex interrelationships between these factors, an analytic approach is not suitable to assess the accuracy of temporal error and of the occupancy prediction. A module is developed to simulate the temporal error and occupancy prediction performance under hypothetical scenarios.

### 6.4.3 Hypothetical scenario test-bed module

The aim of this module is to enable the assessment of the effect of enhanced prediction accuracies on the occupancy predictions of the airspace sectors. To do this, this module assesses the occupancy prediction errors with modified temporal prediction accuracies of selected flows e.g. occupancy error resulting from increasing the accuracy of London departures. Track data and EFD for the non-selected flows are kept constant (Figure 6-14).
This approach enables quantifying the benefits to the ASM/ATFCM function performance by increased predictability concepts e.g. 4D trajectory. With this module structure any enhanced predictability scenario can be tested, such as Aircraft Derived Data (ADD) and Airport-Collaborative Decision Making (A-CDM). In this thesis the module is used in an A-CDM scenario air traffic scenario. The reason is two-fold:

1. Hypothetical on-ground scenarios are more complex than airborne scenarios, since the new test-bed parameters affect the ground and the airborne segment of the predicted trajectories, whilst the airborne just affects the airborne segment. Therefore, the potential capabilities of the framework module are better proved.
2. As discussed in CHAPTER 7, ground predictability is a major source of airspace traffic prediction inaccuracies, hence results from this case study are especially significant.

The A-CDM concept is one of the fundamental pillars of the SESAR program. It is expected
to increase situational awareness between relevant airport stakeholders, which will enable better predictability while the aircraft is on the ground. In turn, ACCs will benefit from this improved predictability through a more accurate pTOT.

The following sections introduce the definition of the hypothetical scenario and detail how the parameters of the hypothetical scenario lead to the re-computation of the EFD.

6.4.3.1 Hypothetical scenario definition

The hypothetical scenario analysis is performed based on the original EFD and track data for a given period of time. The flights belonging to the flow specified by the user (hypothetical flow) are recalculated based on new predictability parameters. Two parameters define the predictability of the hypothetical flow:

- The accuracy of the hypothetical predictions.
- The LAT of the hypothetical predictions.

In order to avoid a deterministic approach for the analysis, probability distributions are used to characterise these features. In addition, this approximates better to real air traffic operations. In fact, (Tobaruela et al., 2014a) show that both the accuracy of the prediction and the LAT of enhanced predictability concepts such as the A-CDM case follow temporal distributions i.e. accuracy and LAT expand over a range of values. As an example, this paper assumes normal distributions if the distribution of the accuracy and LAT of the predictions is not known in advance. Five parameters are needed to define this scenario:

1. Hypothetical flow.
2. Average LAT of the new predictions ($\mu_{LAT}$).
3. Standard deviation of the LAT of the new predictions ($\sigma_{LAT}$).
4. Average error of the new predictions ($\mu_{Error}$).
5. Standard deviation of the error of the new predictions ($\sigma_{Error}$).

$\mu_{Error}$ and $\sigma_{Error}$ define the hypothetical scenario prediction accuracy ($Error_{new}$), while $\mu_{LAT}$ and $\sigma_{LAT}$ define the LAT associated with the new prediction ($LAT_{new}$).
Based on these parameters, the predictions of the flights belonging to the hypothetical flow are simulated as detailed in the paragraphs below. The predictions of the flights not corresponding to the hypothetical flow remain unchanged.

### 6.4.3.2 Hypothetical scenario generation

The approach for the recalculation of the trajectory is similar to the one used in (Brennan et al.), where the effects of various delays are tested: the delays of flights delayed by a regulation is suppressed to determine the performance of those flights without the regulation. A similar approach is used in this module where new predictions are made to test the impact of the accuracy of the TP on occupancy under the conditions defined by the hypothetical scenario.

The re-computation of the trajectories is based on random values drawn from the independent distributions defined for the hypothetical prediction accuracy \(\text{Error}_{\text{new}}\) and the LAT of the hypothetical prediction \(\text{LAT}_{\text{new}}\). These values are automatically generated by the `Hypothetical_Scenario_Tester.m` function (Section 6.5).

The trajectory re-computation is achieved in three steps: Deletion of the original trajectory predictions after the \(\text{LAT}_{\text{new}}\) and before the ATOT (time-frame when hypothetical predictions are added), insertion of the new pTOT and recalculation of the trajectory prediction error.

This process is applied to the trajectory shown in Table 6-6 as an example, using the parameters in Table 6-7. The original predicted trajectories are shown in white. The row highlighted in green corresponds to the new prediction. The row in red corresponds to the original prediction that was deleted. In this table, the \(\text{pTime}\) column indicates when a prediction is made, the second column indicates the pTOT or ATOT depending on whether the flight is on the ground or airborne respectively. The third column indicates the predicted entry times to each of the airspace sectors.
Table 6-6 EFD re-computation example

<table>
<thead>
<tr>
<th>pTime</th>
<th>pTOT/ATOT</th>
<th>Sector</th>
<th>pETI</th>
<th>pXTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:41:57</td>
<td>09:45:00</td>
<td>RHLO-10:04:57-10:08:46/DELLO-10:08:46-10:31:21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06:30:17</td>
<td>09:43:00</td>
<td>RHLO-10:04:59-10:03:13/DELLO-10:03:13-10:25:52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:01:25</td>
<td>10:01:00</td>
<td>RHLO-10:16:05-10:19:51/DELLO-10:19:51-10:42:30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-7 Example of hypothetical scenario parameters

<table>
<thead>
<tr>
<th>Hypothetical Scenario Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothetical flow</td>
<td>EGLL</td>
</tr>
<tr>
<td>µLAT (relative to ATOT)</td>
<td>-1200s</td>
</tr>
<tr>
<td>σLAT</td>
<td>500s</td>
</tr>
<tr>
<td>µError</td>
<td>0s</td>
</tr>
<tr>
<td>σError</td>
<td>500s</td>
</tr>
</tbody>
</table>

Running the module through the Hypothetical_Scenario_Tester.m function (Section 6.5), the following random values are returned: LAT\textsubscript{new} = 1581.7s and Error\textsubscript{new} = -118.2 s.

The three-step process is explained in detail below:

1. Deletion of original predictions after the LAT\textsubscript{new} and before the ATOT.

Predictions before the LAT\textsubscript{new} remain unchanged until the new prediction at LAT\textsubscript{new} is received. In the same manner, predictions after the ATOT remain invariable as they are based on airborne radar position reports, which the A-CDM process no longer has an influence on. Therefore only the predictions after the LAT\textsubscript{new} and before the TOT are eliminated.
2. Creation of a new pTOT at LAT\textsubscript{new}.

At LAT\textsubscript{new} a new prediction is filled for the flights within the hypothetical flow based on the last trajectory before LAT\textsubscript{new} with a new error equal to the random value returned by \textit{Hypothetical\_Scenario\_Tester.m} function i.e. \textit{Error\textsubscript{new}}.

3. Recalculation of the new introduced trajectory based on \textit{Error\textsubscript{new}}.

The recalculation step only affects the pTOT, pETI and pXTI of the TP i.e. the temporal dimension of the newly introduced prediction in the second step. The sector sequence remains invariable. The new pETI and pXTI are based on the last available prediction before the LAT\textsubscript{new} and reflect the effect of \textit{Error\textsubscript{new}}.

Figure 6-15 depicts the effects of the \textit{Error\textsubscript{new}} on the TP accuracy for the different LATs. The impact of the new prediction is restricted to the time-frame after the LAT\textsubscript{new} and before the ATOT (dashed rectangle). Outside the dashed rectangle the original and the re-computed trajectories are the same.

![Figure 6-15 Original (red line) and new (blue line) temporal error accuracy.](image)

The predicted times over each characteristic point along the trajectory are recalculated. Each trajectory is divided into two segments (Tobaruela et al., 2014a):

- The ground segment, which embeds the trajectory from the push back to the take-off.
- The airborne segment, which includes the portion of the trajectory from the push back
until the flight flies over the characteristic trajectory point.

The error at each characteristic trajectory point can be therefore expressed as the error introduced by the prediction of the take-off time (the error of the ground segment) and the error introduced by the prediction of the trajectory time from the take-off time to the time over the characteristic trajectory point (the error of the airborne segment).

This approach to the TP error is mathematically expressed as shown in [6-6] (Tobaruela et al., 2014a):

\[
\text{TP Error} = \text{Error}_{\text{ground segment}} + \text{Error}_{\text{airborne segment}}
\]  

[6-6]

In the case of the A-CDM hypothetical scenario, the only error is associated with the pTOT. The error introduced by the airborne segment remains unchanged. The ground segment error is therefore added to the original prediction. [6-7], [6-8] and [6-9] capture the modification of the baseline values (superscript “0”) to compute the new predicted values for the pTOT, entry and exit times to airspace sectors (where “i” indicates the airspace sector in the predicted sector sequence).

\[
pTOT^{\text{new}} = pTOT^0 + (Error_{\text{new}}^\text{ground} - Error^0_{\text{ground}})
\]  

[6-7]

\[
pETI_{i}^{\text{new}} = pETI_{i}^0 + (Error_{\text{new}}^\text{ground} - Error^0_{\text{ground}})
\]  

[6-8]

\[
pXTI_{i}^{\text{new}} = pXTI_{i}^0 + (Error_{\text{new}}^\text{ground} - Error^0_{\text{ground}})
\]  

[6-9]

pTOT^0, pETI_i^0 and pXTI_i^0 do not exist when there is no prediction prior to the LAT_new. This situation is more likely to occur for large LAT_new values defined in the hypothetical scenario parameters. When this occurs the new trajectory is not recomputed and the predictions of the trajectory will be the same as the original EFD. This effect is considered negligible since, as shown in Figure 6-13, for LATs smaller than 240 minutes, more than 96% of the flight plans have been tactically activated (Figure 6-13), thus predictions typically exist within the EFD.
The previous sections have developed the theoretical basis for the predictability framework. The following section outlines the accomplishment of the automatic implementation of each of the framework modules through Matlab functions (.m files).

6.5 Predictability Framework Implementation: Tools

As discussed in the previous sections, the predictability estimation framework is formed of different modules with specific functionalities. Each of the modules is implemented through a set of programming functions, whose combination and use is selected depending on the concrete objectives for the use of the predictability framework. These programming tools are implemented in a Matlab environment and described below.

Figure 6-16 shows the links between the different Matlab functions that are used within the data generation and error calculation framework to obtain the occupancy prediction and the temporal prediction error results.

The paragraphs below summarise each of the Matlab functions within the data generation and error calculation modules.
The aim of this function is to compile raw data, specifying the interval period of the analysis, and producing a new data set able to be read by the rest of the predictability framework functions.

The inputs for this function are:

- The raw EFD files
- The raw flight tracks
- The period of time for which the data is generated

This function prepares the data set to be used by the rest of the functions based on the raw EFD and Flight Tracks data (data pre-processing). This data set can be used to analyse the temporal error or the occupancy prediction error.

- **Predictability_Analysis.m** and **EFD_FDPS_analysis.m** functions

The **EFD_FDPS_analysis.m** calculates the values for the first sector in the sector sequence only, while the **Predictability_Analysis.m** function calculates this for any sector specified as input to the function. Both functions create the `prediction_times` and the `prediction_times_cells` matrices, which contain the pTOT, pETI and pXTI for each prediction in the EFD of individual flights.

The `prediction_times` and `prediction_times_cells` matrices generated by these functions allow the predictability of each flight to be evaluated.

- **averages.m** function

The **averages.m** function computes the statistical evolution of the temporal error based on the `prediction_times` and `prediction_times_cells` matrices. The rule used for outlier exclusion is specified as an input and can be either 3-sigma, 4-sigma or 5-sigma. The LAT time intervals for the analysis are also chosen by the user. This can be either one-minute (60 seconds) or 5-minutes (300 seconds). The initial and final LAT times of the analysis can be specified although it is recommended to use one day prior to execution to capture the impact of the
flight plan activation.

The figures produced by this function have been customised to depict one-minute and five-minute intervals. Other time intervals can be customised through code adaptation.

- **all_TVs_CHMI_simulator.m function**

This function calculates the one-minute occupancy prediction error of EFD. It evoques an iterative process of the CHMI_simulator function (internal function), which returns the actual and predicted occupancy values for each airspace sector being assessed.

The input to this function is the data set generated by the Data_Period_Generator.m function. It returns the occupancy error for each airspace sector for LATs up to one day. If the contribution of a specific flow is being assessed, the function allows the independent assessment of specific traffic flows.

- **Hypothetical_Scenario_Tester.m function**

This function creates an equivalent data set to the one produced by the Data_Period_Generator.m function but incorporating the modified predictions under the hypothetical scenario parameters. The function inputs are therefore the five hypothetical scenario parameters described in Section 6.4.3.1.

The process following the generation of the hypothetical data set is the same as for the original characterisation of the TP and occupancy prediction error. However, dedicated functions are developed to account for the slight variations introduced by the hypothetical scenario conditions.

- **EFD_FDPS_analysis_HS.m function**

The EFD_FDPS_analysis_HS.m function is the equivalent of the EFD_FDPS_analysis.m function. The structure and flow of the function remain invariant, although it uses as inputs the data set created by the Hypothetical_Scenario_Tester.m function and generates the prediction_times and prediction_times_cells matrices based on the hypothetical data set.
• *all_TVs_CHMI_simulator_HS.m* function

This function is the equivalent of the *all_TVs_CHMI_simulator.m* function. The same structure and flow as in the *all_TVs_CHMI_simulator.m* function applies here, although the new hypothetical data set created by the *Hypothetical_Scenario_Tester.m* function is used.

Other functions are developed to support the user in analysing and assessing the results generated by the main functions. Although these functions do not represent the core of the predictability framework tools, they enable a fast and automated depiction of key results and are therefore briefly discussed in this section.

• *Paint.m* function

This function automatically plots the occupancy prediction error results of the hypothetical scenario testing functional frame.

• *dynamic_error.m* function

This function generates a set of subplots for each airspace sector being assessed, in which the occupancy prediction error as a function of the LAT is depicted for the specified time period of the day (one example in Figure 6-12). Every 0.5 seconds the tool depicts the next minute in the time period of the day. It allows to independently assessing the contribution to the occupancy prediction error generated by the hypothetical flow.

### 6.6 Summary

This chapter has developed a framework to estimate the accuracy of the predictions made by the ETFMS in Europe. This accuracy is a key driver of the performance of the ASM/ATFCM functions, which impact airspace capacity, as it is further discussed in the next chapter.

Both the temporal error and the occupancy prediction error have been quantified within this framework, using three functional frames: data generation, error calculation and hypothetical testing.
The data generation module calculates the predicted times over a characteristic trajectory point and compares these to the actual crossing times using the error calculation module. It was found that, on average, flights are being delayed. The error was found to be highly variable, with two distinct segments: the ground segment, for which the predictions rely on inaccurate flight plans, which express the airspace user intentions, and the airborne segment, for which the predictions are based on actual track positions, with enhanced accuracy.

This has significant implications for airspaces where a high proportion of flights are on the ground until shortly before entering the given airspace, such as is the case for the MUAC (Figure 6-17). In a typical day in the MUAC, the average proportion of airborne flights for all the sectors as a function of the LAT does not exceed 50% until 20 minutes prior to entry in the first MUAC sector. This effect results in different performance characteristics for lower and upper sectors of the MUAC airspace.

![Figure 6-17 Ratio of airborne flights as function of LAT for the MUAC airspace](image)

A module has been developed to assess the effects of enhanced predictability concepts on air traffic predictability, with a focus on enhanced ground predictability. The assumptions for the re-computation of the trajectories have been discussed.

Due to the user-oriented focus of the framework, supporting software for its automatic execution has been developed, detailing the functionality of each function and the relationships amongst them.
The predictability framework has the potential to be used in any ACC as long as the two data sets are available: the EFD and the track data. Generally, the framework can be applied wherever a centralised ATFCM system has been implemented. This is the case for instance in the US, with the deployment of the Enhanced Traffic Management System (ETMS with equivalent functionalities to the ETFMS in Europe (Modzelesky et al., 2001) (Centre, 1995).

The predictability framework can be used during the implementation of modernisation programmes, both to assess the predictability of the airspace as a result of the new implementations and to estimate the potential benefits of the introduction of future implementations.

These two applications of the predictability estimation framework are discussed and applied in the next chapter.
CHAPTER 7  EVALUATION AND APPLICATION OF THE PREDICTABILITY FRAMEWORK

The objective of this chapter is to evaluate and apply the predictability (ASM/ATFCM) framework area.

Figure 7-1 Airspace capacity estimation framework (focus of this chapter highlighted in blue)

This chapter evaluates the performance of the predictability estimation framework developed in CHAPTER 6 through its application to different case studies. Section 7.1 evaluates the predictability framework, divided into the evaluation of the temporal error and the evaluation of the occupancy prediction error. In both of these groups, the evaluation is accomplished in an A-CDM environment to demonstrate the potential of the framework.

Section 7.2 discusses two applications of the predictability framework: feasibility assessment of the implementation of new concepts and quantification of predictability buffer.

For the former, the SESAR OIs associated with enhanced predictability are reviewed and the suitability of the framework to estimate their performance is discussed. For the latter, a methodology for quantifying the predictability buffer is developed and applied to the MUAC DELTA sectors.
7.1 Hypothetical Scenario Module Evaluation

A performance evaluation of the hypothetical testing functional frame is carried out in this section. An A-CDM case study is selected for the performance evaluation due to the significant implications that ground predictability has on temporal prediction error (CHAPTER 6).

The operational performance of Dusseldorf airport (EDDL – ICAO code) is evaluated for April 29, 2013, four days following the implementation of A-CDM with the introduction of the DPI messages (Koolen, 2012).

DPI messages are sent prior to a flight’s departure as information becomes available and increasingly accurate. The DPI messages are divided according to time-to-execution and message focus (Koolen, 2012):

- EDI – Early DPI: amends the flight plan departure slot in case of airport constraints (e.g. ATFCM regulation).
- TDI – Target DPI: refines the Target Take-Off Time of the flight based on the information shared by airport actors such as the ground handling agents.
- TSA – Target StArt-up DPI: communicates the start-up time of the flight.
- ADI – Advanced-DPI message: is sent after the flight Actual Off-Block Time (AOBT) and the aircraft is under the control of the ATC in the tower. The latest updates of the flight are incorporated in this message.
- Finally the Cancel – DPI (C-DPI) message is sent to cancel previously sent DPI messages.
This chapter assesses the effect of the introduction of the DPI messages on prediction error, by comparing flight predictability with and without DPI messages. Two different data sets are used for the performance evaluation: the *original* data set and the *baseline* data set (Figure 7-3).

The original data set is formed of the original EFD and flight tracks. The prediction error results obtained from the analysis of this data reflects the actual predictability of the EDDL flights going through MUAC (Figure 7-3). The original data set is also used to estimate the prediction error performance of the flights with hypothetical DPI messages (hypothetical scenario), using the three-step trajectory re-computation process introduced in Section 6.4.3 (Figure 7-3).

The baseline data set is obtained by excluding the DPI messages from the original data set. It represents the estimated performance of the predictability for the day. It is therefore expected that in the original scenario, the predictability is better than in the baseline scenario.
Table 7-1 shows the observed frequency of each DPI message in EDDL. Due to the low frequency of the TDI, the effect of this DPI message is excluded from the performance evaluation. According to an SME from the Eurocontrol NM the ADI is expected to result in the largest benefits. Thus, the ADI is included in the performance evaluation analysis. Finally, the EDI message is as well evaluated to assess the potential benefit of a large LAT DPI message, which should be ubiquitous in the long-term ATM system.

<table>
<thead>
<tr>
<th>Message</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDI</td>
<td>136</td>
</tr>
<tr>
<td>TDI</td>
<td>53</td>
</tr>
<tr>
<td>TSA</td>
<td>214</td>
</tr>
<tr>
<td>ADI</td>
<td>131</td>
</tr>
</tbody>
</table>

The Hypothetical_Scenario_Tester.m Matlab function (Section 6.5) of the hypothetical testing framework module requires to define the hypothetical scenario parameters: hypothetical flow $\mu_{LAT}$, $\sigma_{LAT}$, $\mu_{Error}$, $\sigma_{Error}$. These parameters are estimated from actual data of EDDL operations on the day of analysis (Table 7-2).
The mean and standard deviation of each four distributions in Table 7-2 are used as input parameters for the hypothetical scenario definition.

The two sections below compare the three scenarios (original, baseline and hypothetical) for the temporal error and occupancy prediction errors on the basis of the ADI and EDI.

### 7.1.1 Temporal prediction error

#### 7.1.1.1 Advanced-DPI message evaluation

The average (continuous line) and standard deviation (dashed line) of the temporal error for EDDL departures flying through MUAC airspace is shown in Figure 7-4 for the three scenarios.
The temporal error performance of the three scenarios converges for LATs larger than 40 minutes. The ADI message is typically sent on average 11 minutes before TOT and therefore predictions are increasingly less influenced by the ADI messages for larger LATs.

The error of the predictions under the three scenarios converges as well for LATs of less than 10 minutes. It takes on average 10 minutes from TOT to enter the first MUAC sector, therefore around LATs equal to 10 minutes, the first messages derived from radar tracks are received (e.g. CPR), predictions are updated with this information and not rely anymore on DPI predictions.

The comparison of the baseline and the actual scenarios show the positive effect of the ADI message on the temporal error performance both in terms of the average error and the standard deviation. Both are significantly reduced by the introduction of the ADI message.

The enhancement caused by the introduction of the ADI message in the temporal error performance is accurately captured by the hypothetical scenario. Larger standard deviations can be observed though which are originated by the approximation of the messages by normal distributions and other data manipulation issues by the ETFMS not replicated by the framework (Table 7-2). This approximation is conservative since, as shown in Section 7.2.2, the latent airspace capacity is inversely proportional to the value of the standard deviation.

Figure 7-4 – ADI temporal prediction error evolution (continuous line – average; dashed line
7.1.1.2 Early-DPI message evaluation

Figure 7-5 shows that the effect of the EDI message in the temporal error is on average negative. The baseline scenario, in which the EDI messages have been suppressed, has a smaller temporal error than the original scenario.

This is a major finding since it indicates that flight plans are more reliable than the predictions made based on the A-CDM process outputs and suggests that until further prediction accuracy improvements in the EDI message, this should be ignored.

The application of Error! Reference source not found. to EDDL departures shows an average value of $\mu = 19.8$ s and a standard deviation of $\sigma = 102.8$ s. These values suggest that the introduction of the EDI message in comparison to the previous flight plan prediction in the ETFMS, does not yield any predictability benefit and even degrades the accuracy of the predictions.
Figure 7-5 captures this effect although showing a worse performance than in the original scenario. This is attributed to the incorrect approximation by normal distributions in Table 7-2, and makes the results under the hypothetical scenario conservative.

7.1.2 Occupancy prediction

The occupancy prediction is characterised for one particular airspace sector. All the MUAC DECO sectors combined (the largest operational sector) are used for the evaluation to capture the maximum amount of traffic (see Appendix 4). It is assumed that with the larger amount of traffic, the errors of the occupancy predictions will be greater than for small operational sectors with lower air traffic levels.

As discussed in Section 6.4.2.2, the occupancy prediction error is a function of the LAT and of the time of the day at which the occupancy is being calculated. When the occupancy is low (i.e. typically during night times), the error of the occupancy tends to be negligible.

On the other hand, when the traffic is higher, the occupancy error is greater, indicating that the occupancy error is proportional to the actual occupancy. In the evaluation the focus is on high traffic scenarios between 06:00 UTC and 20:00 UTC.

The occupancy prediction error for the ADI and EDI messages and the corresponding three scenarios are analysed in the two sections below.

7.1.2.1 Advanced-DPI message evaluation

The performance evaluation of the ADI message occupancy prediction error for the three scenarios is depicted in Figure 7-6 (continuous line for the mean value and dashed line for the standard deviation). Similarly to the temporal error evolution, the performance of the three scenarios converges for LATs smaller than 10 minutes and greater than 40 minutes. In these periods the effect of the ADI message is negligible due to the typical broadcasting time of the message (Table 7-2).

Results show that even in the time-frame of 10-40 mins LAT, when the ADI message should more significantly impact the occupancy prediction error, the standard deviations and
especially the mean errors of the three scenarios are similar. These findings suggest that the ADI message does not create any real benefit for the occupancy prediction accuracy. This effect is also captured for the hypothetical scenario.

![Graph](image)

**Figure 7-6 – ADI occupancy prediction error for the original, baseline and hypothetical scenarios in the MUAC DECO sectors**

In order to show the impact on the occupancy error, different hypothetical scenarios are created and evaluated.

The LAT distributions are kept the same for this evaluation as for the temporal error one, since the ADI message should always be sent within that LAT time-frame ($\mu_{LAT} = -658.9$ s, $\sigma_{LAT} = 173.3$ s). The $\mu_{Error}$ is not expected to be a major contributor to enhanced occupancy predictability. Its main influence is on the temporal error as shown in Section 7.1.1.

For instance, a $\mu_{Error}$ indicating that flights are being delayed would not affect the average occupancy prediction errors as a function of the LAT. Instead, it would show that during the day the occupancy peaks and valleys, regardless of their absolute occupancy error, will occur later in the day. This phenomenon is the so-called *rolling-spyke* (Hoffman et al., 1998).

Therefore, the $\sigma_{Error}$ is the main occupancy prediction error driver. The occupancy prediction
error is evaluated for a $\sigma_{\text{Error}}$ of 0, 3, 5 and 10 times the one defined for the hypothetical scenario ($\sigma = 628.1$ s). Results are shown in Figure 7-7.

Increasing values of $\sigma_{\text{Error}}$ show an increased standard deviation of the occupancy error, as expected. However, the variations of the $\sigma_{\text{Error}}$ have to be large (more than 5 times larger) in order to obtain significant occupancy prediction benefits. For the $\sigma_{\text{Error}}=0$ case, which has been calculated with $\mu_{\text{Error}}=0$ as the optimum scenario, it is observed that the standard deviation error reduction in comparison to the original case (blue line) is almost negligible.

This result indicates that the gains to be released by an enhancement of the predictions due to the introduction of ADI messages with low variability are not expected to be significant.

### 7.1.2.2 Early-DPI message evaluation

Figure 7-8 shows the occupancy prediction error for three scenarios with EDI messages at different LATs.
The error evolution of the occupancy prediction is almost identical under the three scenarios. The hypothetical scenario slightly overestimates the standard deviation, i.e. it is conservative.

Similar to the ADI performance evaluation, the EDI message was not found to have any significant benefit on the occupancy prediction performance for the tested parameters. This indicates that this message would only release significant prediction accuracy benefits under an extremely predictable environment, not envisaged to occur in the near future.

7.2 Predictability Framework Applications

The developed framework has two direct applications for capacity estimation:

- Assessment of the quality of the predictions that are used by the ASM and ATFCM functions.
- Quantification of the predictability safety buffers and the latent airspace capacity.

The sub-sections below introduce the general methodology for the application of the framework and apply it to concrete case studies. In addition, a mapping between SESAR OIs
and the predictability framework is achieved in order to demonstrate its applicability in the modernisation of ATM.

7.2.1 Feasibility assessment of new concepts implementation

This section determines the SESAR OIs to which the predictability framework can potentially be applied to estimate the OI’s benefits. The different OIs are grouped in categories in terms of the key focus area of the enhancement: airport processes information sharing, trajectory information sharing and airspace operations.

There are three approaches to increasing the accuracy of air traffic predictions: sharing higher-accuracy information (Section 7.2.1.1) and improving the accuracy of the prediction models (Section 7.2.1.2) or reducing air traffic flexibility in order to force flights to meet all trajectory constraints (Section 7.2.1.3).

7.2.1.1 Airport processes information sharing

This group of OIs is characterised by the enhancement of ground predictability by means of more dynamic and transparent airport information sharing processes. These processes are integrated within the A-CDM concept. Table 7-3 captures the OIs within this category.
### Table 7-3 – List of SESAR OIs with enhanced ground information sharing processes

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OI step</th>
<th>IOC</th>
<th>FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUO-0201</td>
<td>Enhanced flight plan filling facilitation</td>
<td>31-12-2011</td>
<td>31-12-2014</td>
</tr>
<tr>
<td>DCB-0301</td>
<td>Improved consistency between airport slots and flight plans</td>
<td>31-12-2012</td>
<td>31-12-2015</td>
</tr>
<tr>
<td>AO-0501</td>
<td>Improved operations in adverse conditions through A-CDM</td>
<td>31-12-2007</td>
<td>31-12-2013</td>
</tr>
<tr>
<td>AO-0601</td>
<td>Improved turn-round process through CDM</td>
<td>31-12-2010</td>
<td>31-12-2016</td>
</tr>
<tr>
<td>AO-0602</td>
<td>Collaborative pre-departure sequencing</td>
<td>31-12-2010</td>
<td>31-12-2016</td>
</tr>
<tr>
<td>AO-0603</td>
<td>Improved de-icing through CDM</td>
<td>31-12-2010</td>
<td>31-12-2016</td>
</tr>
<tr>
<td>AO-0801</td>
<td>Collaborative airport planning</td>
<td>31-12-2014</td>
<td>31-12-2019</td>
</tr>
<tr>
<td>AO-0802</td>
<td>A-CDM process enhanced through integration of landside process outputs</td>
<td>31-12-2014</td>
<td>31-12-2019</td>
</tr>
<tr>
<td>DCB-0304</td>
<td>Airport CDM extended to regional airports</td>
<td>31-12-2014</td>
<td>31-12-2017</td>
</tr>
<tr>
<td>AO-0803</td>
<td>Integration of airports into ATM through management of airport transit view</td>
<td>31-12-2017</td>
<td>31-12-2021</td>
</tr>
</tbody>
</table>

The final aim of increased ground predictability is to provide more reliable TOT predictions, which are fundamental to air traffic predictability (Section 6.4.2.1).

AUO-0201 focusses on a more accurate flight plan filling process in which airspace users reflect not only their preferred operations but also the reality of airspace constraints. DCB-0301 shares the same focus by increasing the consistency between flight plans and airport slots. No insight is provided into how this may be achieved. Other OIs provide more pragmatic solutions increased information sharing, and these are explained below.

AO-0501 promotes the sharing of information on large disruptions to the system (e.g. weather storms or industrial actions) and updates the trajectory to account for these disruptions. In today’s system this information is not dynamically updated. This is illustrated in Figure 7-9 where dashed lines represent the standard deviation of the temporal prediction error and the continuous lines the average errors for various levels of disruptions.

The days represented in green are 16, 17 and 18 of January 2013. During these days, operations at Amsterdam airport (EHAM – ICAO code) were normal with no associated...
delays. The red lines represent the temporal error on 15 January 2013. On this day the Amsterdam Flight Information Region (FIR) created 38% of the European delay with an average delay per flight of 76.59 minutes (Eurocontrol, 2014).

This effect can be seen through the EHAM departures temporal error. The mean error on 15 January 2013 shows a large deviation from the other three normal-operations days. The mean error shows significantly larger delays than during nominal operations, as expected.

AO-0601 and AO-0802 focus on the turn-around and landside processes. In the current ATM system, both processes are usually not visible to the ATM stakeholders. However, an increased awareness of the state of the turn-around and landside activities can potentially extend the predictability horizons for flights on the ground.

For instance, if the payload loading process to the aircraft is delayed due to a delayed baggage transfer, the flight will not push back until the baggage transfer is complete (provided that the AOC considers it appropriate to wait for this additional baggage). The ground handlers and the AOC involved in the turn-around process are aware of this delay and, if shared with the rest of the ATM stakeholders, the predictions across the ATM system can update and delay this flight to meet the arrival time of the missing baggage.

Figure 7-9 – Effect of large delays on EHAM airport departures
Similarly to the previous OI, AO-0603 incorporates information on processes carried out on the ground. The de-icing process can lead to longer turn-around times or longer taxi-times and sharing this information is expected to improve predictability.

A better knowledge and awareness of the ground processes through the A-CDM concept can potentially be translated into a strategic management of the flight departures sequence (AO-0602). In current operations, flights, after push back, taxi to the runway where they queue until a slot is assigned to them. This is accomplished on a First-Come-First-Served basis. However, the actual sequence very frequently differs from the one contained in the predictions. An increased accuracy of the departure sequence can produce more accurate TOT estimations, hence increased predictability.

AO-0801 predicts the flights that will frequent the airport based on the information available on the air transport network state. For instance, if the current state of the network shows that flights are being delayed due to airports in other regions being closed, AO-0801 will assess the impact on the airport processes and affected flights. For example, it will evaluate whether a sudden increase in the number of arrivals will occur when the other airports are re-opened and whether flights will be delayed due to insufficient airport stands. This OI step will be supported in the long-term by other OI steps such as DCB-0304 and AO-0803, which will integrate the airport processes into the network and vice-versa.

The impacts of these OIs on the temporal and occupancy prediction accuracy can be assessed with the predictability framework developed in CHAPTER 6. The performance of the OIs can be captured with the hypothetical scenario parameters (Section 6.4.3.1) and air traffic predictability performance can subsequently be estimated with the Hypothetical_Scenario_Tester.m function (Section 6.5).

### 7.2.1.2 Trajectory information sharing

This group captures OIs that are expected to contribute to higher predictability levels through the sharing of more accurate trajectory information. Table 7-4 captures the OIs within this category.
Table 7-4 – List of SESAR OIs with enhanced trajectory information sharing processes

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OI step</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS-0101</td>
<td>Improved flight plan consistency pre-departure</td>
</tr>
<tr>
<td></td>
<td>31-12-2007 31-12-2010</td>
</tr>
<tr>
<td>IS-0102</td>
<td>Improved management of flight plan after departure</td>
</tr>
<tr>
<td></td>
<td>31-12-2009 31-12-2012</td>
</tr>
<tr>
<td>DCB-0302</td>
<td>Collaborative management of flights updates</td>
</tr>
<tr>
<td></td>
<td>31-12-2010 31-12-2014</td>
</tr>
<tr>
<td>AUO-0203-A,B,C</td>
<td>The business trajectory</td>
</tr>
<tr>
<td></td>
<td>2016 2025</td>
</tr>
<tr>
<td>AUO-0204-A,B,C</td>
<td>Use of Aircraft Derived Data (ADD) to enhance ATM ground system performance</td>
</tr>
<tr>
<td></td>
<td>31-12-2018 31-12-2023</td>
</tr>
<tr>
<td>IS-0302</td>
<td>Automatic RBT update through Trajectory Management Requirements (TMR)</td>
</tr>
<tr>
<td></td>
<td>31-12-2020 31-12-2025</td>
</tr>
</tbody>
</table>

IS-0101, IS-0102 and DCB include a dynamic management and sharing of flight updates before and after departure as information becomes available. These updates may affect the flight plan and are shared between all relevant stakeholders. This process is currently occurring through the dynamic updates of the ETFMS (Section 6.3) and therefore no hypothetical estimations are needed.

OIs AUO-0203-A,B,C and AUO-0204-A,B,C are embedded within the business trajectory concept. The core of the business trajectory concept is the shift of the flight plan to a 4D trajectory that is updated as more accurate information becomes available. This information is shared with the stakeholders, which use the latest 4D trajectory to make predictions.

The business trajectory includes airspace user intents, restrictions to the trajectory caused by weather and airspace constraints, and ATC and NM clearances and preferences. The introduction of the business trajectory, replacing current flight plans is expected to produce a significant TP accuracy increase.

In order to enhance predictions, the ETFMS will be fed with new data sources including Aircraft Derived Data (ADD). IS-0302 will gradually overtake the role of the traditional surveillance systems (e.g. radar) for aircraft positioning functions and will include new
information being shared, such as the aircraft intent. Whilst the former is not expected to produce significant benefits (in Section 6.4.1.1 the ARTAS error was shown to be negligible) the latter is the main enabler for enhanced predictability.

IS-0305 will be an enabler for updating the predictions of airborne flights when deviations from the agreed trajectory occur. This approach will avoid periodic updates and only when thresholds are reached, new predictions will be made.

These OIs can be evaluated with the predictability estimation framework through the formulation of appropriate hypothetical scenarios. These concepts are expected to mainly impact the airborne segment of the trajectory, as for the A-CDM concept.

### 7.2.1.3 Air traffic procedures

New air traffic procedures can directly impact the predictability of air traffic. In fact, some OIs aim to increase the accuracy of air traffic by carrying out procedures that are more predictable as explained below. This is usually associated with a decrease in the flexibility of operations.

An example of this trade-off is the free-routing environment: airspace users can optimise their trajectory to achieve efficient operations. The most efficient trajectory can change dynamically, due to airspace constraints (e.g. other traffic). The dynamic change of the trajectory can subsequently reduce the predictability of the flight. Table 7-5 captures the OISs within this group.

Table 7-5 – List of SESAR OISs introducing new air traffic operations leading to enhanced predictability

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OI step</th>
<th>IOC</th>
<th>FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS-0103</td>
<td>Controlled Time of Arrival (CTA) through use of datalink</td>
<td>31-12-2020</td>
<td>31-12-2023</td>
</tr>
<tr>
<td>TS-0303</td>
<td>Arrival management extended to en-route airspace</td>
<td>31-12-2017</td>
<td>31-12-2020</td>
</tr>
</tbody>
</table>

294
OIs will increase the prediction accuracy of air traffic operations to meet the envisaged predictability levels for future increased air traffic demand scenarios (Schuster, 2015). Rigid operations (as opposed to flexible operations) will be introduced in anticipation to traffic congestion areas to ensure sufficient air traffic organisation (TS-0303).

A specific implementation will be the introduction of the Controlled Time of Arrival (CTA) (TS-0103). The CTA corresponds to time constraints for flights at given airspace points to organise the operations in congested airspace, fundamentally TMAs, at the expense of reduced flexibility. The framework developed in this chapter supports the assessment of this modernisation initiative through a scenario that assigns a zero-error (or within CTA tolerances) at certain points in the trajectory.

7.2.2 Quantification of the predictability buffer

ACCs have to reserve fractions of their capacity to account for unforeseen traffic peaks (EUROCONTROL, 2005). The traffic peaks occur due to inaccurate air traffic predictions, and specifically occupancy predictions: the larger the risk of the occurrence of these peaks, the larger the allocated buffer.

In the current ATM system, airspace sectors can only handle a limited number of flights. This is expressed in terms of throughput or occupancy (Section 3.1) and is referred to as the declared capacity. However, these declared capacities, are lower than the ATC capacity (CHAPTER 4) in order to account for the uncertainty of unforeseen additional demand (Dalichampt, 2006).

This capacity buffer may potentially be used to increase future capacity if the buffer margins can be reduced. The ASM and ATFCM functions apply measures and solutions in order to ensure that air traffic demand will not overshoot the declared capacity. An increase in this declared capacity could therefore be translated into an effective increase of controlled air traffic demand in a scenario where demand is constrained by declared capacity.

The amount of this predictability buffer or latent capacity (Tobaruela et al., 2014a) is therefore proportional to the amount of unexpected demand [7-1]: the larger the unforeseen demand the greater the capacity margin needs to be to ensure that no over-deliveries will
occur. Ideally, if air traffic predictions were completely accurate, the predictability buffers would be reduced to zero, since all the demand would be accurately predicted.

\[ \text{Buffers}_{\text{predictability}} \propto \text{prediction inaccuracy} \]  

Discussions with MUAC and Skyguide FMPs and EOS staff showed that these predictability buffers are not analytically calculated at an ACC level. However, based on the experience accumulated by FMPs, the declared capacities are gradually amended in order to account for the unforeseen demand.

Calculating the magnitude of the predictability buffer is of crucial importance to estimate the predictability enhancements on airspace capacity. However, this type of analysis has been generally overlooked. The most relevant study to the date is (Iagaru et al., 2010). This Eurocontrol study attempts to calculate the airspace capacity benefits, in occupancy terms, of the A-CDM concept implementation.

The (Iagaru et al., 2010) approach is based on a set of simulations in which the performance of EDDM (the only airport with A-CDM at the time of the study) is extrapolated to other airports, in which A-CDM performance is assumed. The level of the saturation of the airspace sectors and the risk of exceeding the declared capacity is calculated.

Under enhanced predictability conditions, the risk of overloading the sectors is reduced and therefore capacity enhancements can be achieved. The study concludes that capacities could be raised to 1 to 2 aircraft per sector corresponding approximately to a 10% of capacity increases.

The study provides a first attempt to quantifying airspace predictability benefits, although two fundamental assumptions are made:

- The predictability buffer is not a function of the LAT.

In other words, it does not account for the fact that the inaccuracy of the prediction is a function of the LAT (CHAPTER 6) and tends to increase for large LATs. However, the decision to regulate or change an airspace configuration is only made by FMPs in a narrow
time interval. It is precisely during this period (60 minutes as later defined) when the predictability inaccuracy becomes relevant.

- The overload risk value is fixed.

The study assumes that if more than 95% of the predictions are within the defined capacity limits, operations remain safe. However, this value may vary according to the impacts of an over-delivery for a given airspace sector.

In order to address the above deficiencies, a methodology is proposed below for the estimation of the predictability buffers. The methodology is based on historical occupancy prediction errors and the results are applicable to a single airspace sector. It is formed of the following steps:

1. Definition of the LAT-decision-time.

The LAT-decision-time is defined as the instant when the FMPs perform ASM/ATFCM measures that protect airspace sectors from over-deliveries i.e. predictability buffers are applied. The FMPs apply safety buffers to the declared capacities in order to account for the demand uncertainties. However, the demand uncertainties are a function of the LAT. In capacity terms, the interest is on those LATs when the ATFCM/ASM decisions are made (the decision time). It is the uncertainty in this LAT-decision-time that contributes to the predictability buffers. During other periods, the uncertainty is less relevant since no FMP ASM/ATFCM related decisions are being made.

The selection of the LAT-decision-time depends on the specific operations of each ACC: non-dynamic ASM/ATFCM operations rely on the decisions made for large LATs (with larger uncertainties), whilst dynamic operations rely on the predictions made in larger LAT intervals, extending from large to short times before the execution.

For the current analysis a LAT-decision-time of 60 minutes is adopted. This value is seen by FMPs as a middle-solution between rigid and dynamic operations.
2. Characterisation of the occupancy prediction distribution error at the LAT-decision-time.

The all_TVs_CHMI_simulator.m function (Section 6.5) is used for this step. This function computes the occupancy prediction error as a function of the LAT and time of the day. Night-times are excluded from the analysis since ASM/ATFCM measures almost do not exist during this period.

At the LAT-decision-time, singularities in the predictions can occur e.g. flawed predictions, thus leading to non-representative safety buffers. In order to avoid such singularities, an interval of +/- 2 minutes around the LAT-decision-time is adopted.

3. Prediction Reliability (PR) ratio definition.

[7-1] indicates that unreliable predictions are translated into larger safety buffers. From an operational point of view, the reliability of air traffic predictions is key to ensuring that the demand/capacity imbalances are correctly predicted. When capacity/demand imbalances are not correctly predicted, the ATC function has to absorb the imbalance and safely control the excess of air traffic demand.

In a hypothetical completely inflexible scenario, any non-predicted capacity/demand imbalance would translate into the degradation of air traffic safety (e.g. through a workload increase above safety limits). In such scenario, air traffic predictions would have to be completely reliable to ensure safety. However this can only be achieved at the expense of very large safety buffers. This indicates that the optimum solution is a combination of reliable air traffic predictions along with a flexible ATC function which can temporarily absorb excesses of air traffic demand.

ACCs already incorporate this notion of temporary increase of demand with the creation of capacity thresholds for sustained periods of time and for short-term periods of time. This allows FMPs to apply lower safety margins, since the ATC is prepared to safely accept temporary over-deliveries.

An indicator is developed in (Tobaruela et al., 2014a) to express the extent of reliability
needed for air traffic predictions: the Prediction Reliability (PR) ratio. The PR ratio is defined as the “ratio of success on predicting the traffic demand within a certain margin of flights error”. This ratio, expressed in % indicates that from the total predictions made, the PR % of those predictions had an error less than a given value.

The occupancy error margin increases as the PR increases, i.e. the error margin for a PR value of 99% will be larger than the error margin for a PR value of 50%.

The definition of the PR has to be estimated from the FMPs based on their knowledge of ATC flexibility.

4. Predictability buffer estimation.

The predictability buffer is the latent capacity or the reduced capacity limited by ATC capabilities to respond to air traffic predictions uncertainties. This buffer corresponds to the PR error margin. Therefore, the definition of the PR ratio is uniquely associated with a safety buffer.

The buffer according to the PR definition is estimated as:

\[
Buffer = \begin{cases} 
|p(100 - S)| & \text{if } p(100 - S) \leq 0 \\
0 & \text{if } p(100 - S) > 0 \quad (\text{cost-efficiency associated})
\end{cases}
\]

[7-2]

where “p” indicates the percentile and “S” the occupancy error value corresponding to the PR ratio in the occupancy error distribution.

This equation shows that occupancy prediction errors overestimating the traffic have an associated buffer of zero. In fact, expecting higher than actual levels of traffic is conservative (theoretically more sectors will be open and more resources employed). However, this uncertainty has an associated cost-inefficiency (Tobaruela et al., 2013).

Traffic under-estimations have safety impacts, and therefore an associated buffer is required to ensure that actual traffic demand does not exceed ATC capabilities. The predictability buffer is calculated as the occupancy error value above which lies the PR% of the
This four-step methodology is applied to the DELTA airspace sector in MUAC airspace. A single day in the week is selected for the analysis to avoid biased results due to traffic patterns corresponding to individual days of the week. Therefore, all Thursdays in July and August are used to compute the occupancy prediction error distribution (Figure 7-10).

![Figure 7-10 Occupancy error distribution](image)

The value of the buffer for the error distribution in Figure 7-10 depends on the selected PR ratio. Figure 7-11 shows the evolution of the buffer (blue line) as a function of the PR ratio. For the computation of this figure, the buffer has been calculated every 1% PR steps. As expected, the buffer increases as the air traffic becomes more reliable.
The relationship between the buffer and PR ratio is expressed by a functional exponential relationship (adjusted R-square=0.9538, least-squares).

\[
\text{buffer} = 0.03293 \cdot e^{0.05603 \cdot S}
\]  \[7-3\]

[7-3] mathematically expresses the trade-off between the capacity and safety.

Figure 7-12 depicts the occupancy error of flights going through MUAC DELTA sector for every Thursday during the summer of the year 2013. Results for other days of the week indicate a similar behaviour of the occupancy prediction accuracy. Therefore, the trend in the error evolution for different days exists for all LATs.
This finding suggests that the quantification of predictability buffer is independent of the day of operations, provided that no major event or action is occurring in the European air traffic network.

Finally, it was noted earlier in this chapter that the traffic levels in the airspace sectors may drive sector predictability. In this regard, it was assumed that large operational sectors would lead to larger inaccuracies and vice-versa. This assumption is confirmed in Figure 7-13.
Figure 7-13 Occupancy predictability error comparison for large (blue) and small (red) operational sectors (continuous line show mean values and dashed lines standard deviations)

Figure 7-13 compares the occupancy predictability between a large sector in blue (DELTA) and a small sector in red (Holstein Low). Both curves are averaged over all Thursdays in the summer of the year 2013.

Improvements in predictability are therefore more relevant for congested operational sectors, where capacity saturation occurs.

7.3 Summary

This chapter has carried out an evaluation of the predictability framework developed in CHAPTER 6. It has discussed the A-CDM concept performance, the feasibility of estimating SESAR OI benefits using the proposed framework and has applied the framework to estimate predictability buffers.

The predictability framework performance was shown to be accurate in estimating hypothetical scenarios predictability performances both in terms of temporal prediction and occupancy prediction. For the evaluation of the former, two case studies were carried out: one with the introduction of ADI messages and the other with the introduction of EDI messages.

The introduction of ADI messages was found to release significant benefits in terms of temporal prediction accuracy, however the benefits of EDI messages on airspace
predictability are less clear. No major differences were found with respect to the baseline “no-A-CDM” scenario.

With respect to occupancy prediction, the predictability framework has accurately captured the increased prediction accuracy, although small deviations were found due to the definition of the hypothetical scenario parameters.

ADI and EDI messages were shown not to have any significant impact on the occupancy predictability in comparison to the baseline scenario. It was shown that even in the ideal case, where ADI messages are sent with zero-error, the benefits would be insignificant. This finding supports the need to introduce a Europe-wide implementation of the A-CDM concept as opposed to its implementation at single airports, where its effect on airspace capacity is diluted by the inaccuracy introduced by traffic flows departing from non A-CDM airports.

The most relevant SESAR OIs in predictability terms were discussed and mapped to one of the following categories: airport process information sharing, trajectory information sharing and air traffic operations. The potential benefits of each of the OIs were assessed using the predictability framework.

Finally, a methodology was developed to quantify the predictability buffer or latent airspace capacity due to air traffic prediction inaccuracies. This methodology was applied in a 3-step process, which defines the LAT of the ASM/ATFCM decisions, subsequently it computes the occupancy prediction evolution using the predictability framework and finally it defines a Prediction Reliability (PR) ratio, which mathematically expresses the risk of having an over-delivery

The predictability buffer was found to be dependent on the PR value, with larger reliabilities leading to larger buffers. In addition, it was proved to be dependent on the sector type, with larger volumes and traffic levels leading to higher buffers. Finally, the predictability buffer was found to be dependent of the LAT, with short anticipation leading to reduced buffers.

The predictability framework developed is the first attempt to quantifying the benefits of enhanced predictability related SESAR OIs on airspace capacity using real operational data, supporting both the assessment of airspace predictability pre- and post- implementation.
through the hypothetical testing framework module.
The objective of this chapter is to develop the workload framework area.

As discussed in CHAPTER 4 ATCO workload has been the major factor in airspace capacity estimations. In addition, as discussed in Section 4.5, ATCO workload is still a major concern for today’s and future operations, provided that the ATCO remains a major actor within the ATM system. In fact, ATCO workload is ultimately the major capacity driver, when the other ATM functions, fundamentally ATFCM and ASM fail to successfully meet their objectives. Therefore, ATCO workload needs to be accurately measured.

In Section 4.2 a review of the existing workload estimation methodologies was achieved. Section 4.4 discussed that the identified methodologies are focused on specific stages of the capacity estimation lifecycle. Furthermore, it was identified that they were not focused on the operational trial and real operations time-frame. The workload methodology developed in this chapter attempts to close this gap.

The methodology developed in this chapter aims to support the feasibility assessment of the
introduction of new procedures, technologies and operational concepts in reducing ATCO workload. The objective is to estimate ATCO workload during operational trials and real time operations. In addition, it is seen that the methodology is further applicable to measure workload during RTS.

Section 8.1 develops the theoretical background for the novel workload estimation methodology. Section 8.2 identifies the data requirements to feed the developed methodology and discusses the meaning of the different data inputs and need for data pre-processing. Section 8.3 explains how the ATCO strategy is identified from the assessment of the data source and how different rules are triggered to compute the perceived complexity associated with each flight (Section 8.4). Section 8.5 associates the total perceived complexity computed value to a qualitative workload level, able to be easily used by operational staff (e.g. EOS). Section 8.6 introduces the process for the calibration of the methodology and presents the calibration results for MUAC DECO sectors.

8.1 Proposed Workload Estimation Methodology

Based on the results of CHAPTER 4, current methodologies for measuring ATCO workload can be divided into two categories: direct and indirect measurement techniques. The former are based on obtaining workload indicators directly from the ATCO. These indicators can be measured during the execution of the exercise or operation (on-line) or post-operations (off-line).

Direct on-line methods interfere with the ATCO operation whilst direct off-line methods are very dependent on individual subjective factors. On the other hand, indirect methods are focused on inferring workload based on air traffic scenario parameters such as complexity or on a modelling of the human performance i.e. FTS. This approach lacks a correct identification of the individual working practices of different ATCOs. Furthermore, it has limitations in the correct identification of the different effects that an air traffic scenario has across different ATCOs due to individual ATCO cognition (Section 3.4.2).

In summary, existing workload measurement techniques, both direct and indirect have a number of deficiencies, which include interfering with the execution of ATCO tasks,
excessive subjectivity, long post-operations analysis and failing to capture the individual ATCO cognitive processes. The methodology developed in this chapter overcomes these existing deficiencies.

In order to develop a novel workload estimation methodology able to overcome the deficiencies identified above, this section starts by revisiting the ATCO workload theory reviewed and discussed in CHAPTER 3. This theory is captured in Figure 8-2.

![Figure 8-2 Workload and cognitive stages (Section 3.4)](image)

In this figure the deficiencies of existing methodologies become apparent:

- Direct on-line methods that are based on interfering with the ATCO performance, subsequently impact upon workload, hence resulting in biased results.
- Direct off-line methods are based on post-exercise memory of workload although this is associated with each particular instant of the operation and its perception.
- Indirect methods relate workload to objective air traffic indicators i.e. the objective complexity (Section 3.4.1). However, they do not capture the intermediate cognitive
As discussed in Section 3.4, workload is initially created by the objective air traffic scenario factors, which include air traffic complexity associated with the flights and structural and system complexity associated with the airspace design and ATC systems. This complexity is perceived differently by individual ATCOs in the information & acquisition cognitive stage. This results in a perceived complexity, which varies across different ATCOs, even with the same air traffic scenario.

Given the magnitude of the perceived complexity, the ATCO chooses amongst a set of strategies with an associated task load. The strategy that more accurately matches the desired workload level is finally implemented. The implementation of the strategy through its associated task load results in an effort or workload, which in turn is affected by the effectiveness of the ATCO performance.

It is obvious from Figure 8-2 that the selection of the strategy is a crucial indicator of the ATCO perception of the air traffic scenario and subsequently of the workload levels. In fact, a very complex scenario is controlled through a very demanding strategy although this differs amongst ATCOs who show more effective strategies depending on their capabilities and therefore, reduced workload. The existence of a relationship between the selection of the strategy and workload is already identified in (Sperandio, 1978, Loft et al., 2007).

In order to estimate workload, the methodology developed here infers a perceived complexity level from the selection of a control strategy. Subsequently, this perceived complexity level is related to a workload level (Tobaruela et al., 2014b).

From a purely theoretical point of view the main assumption within this approach resides in not capturing the effect of performance on workload (Figure 8-2). This effect is associated with the subjective implications that a decreased performance may have on the stress perceived by the ATCO in controlling the traffic and ultimately on workload.

Discussions with MUAC ATCOs during the workload model validation (CHAPTER 9) were held to verify the limitation imposed by this assumption. ATCOs agreed on the existence of a link between performance and workload, although they indicated that under normal
operations, performance is within standards even under high workload levels. These conclusions support the statement of this assumption, although the results of the model may be flawed under non-normal operations.

Figure 8-3 presents the structure of the workload estimation methodology.

Figure 8-3 Workload estimation methodology (Tobaruela et al., 2014b)

The methodology consists of four major stages: data generation, strategy identification, perceived complexity calculation and mental workload estimation. In addition, a calibration task is accomplished to fine tune each of the methodology stages.

Each of the stages is introduced in the sections below.
8.2 Data Generation

The workload estimation methodology developed in this chapter is based on a correct identification of the ATCO working strategy, which in turn can lead to estimating the perceived complexity and finally workload.

The aim is to develop a methodology to be implemented through a tool, which enables the user to carry out automatic workload assessments with short pre-processing and post-processing stages. In order to do this, data for the methodology coming from automated ATC systems is used. This data fundamentally contain the ATCO commands executed during the ATC activity.

This type of data can be gathered as well through observations, for instance through a looking-over-the-shoulder task, identifying the ATCO actions at each moment, or through video recordings. This manual approach is clearly more resource-intensive as it requires a person, ideally an ATCO identifying the other ATCO tasks during a given period.

On the other hand, if this data could be automatically generated from the ATCO activity, the data generation process would be automatically triggered. The automatic data generation is increasingly possible in today’s ATC centres due to the rise in automated ATC systems and subsequent recording and processing of additional data, including the ATCO actions. Interviews with MUAC and Skyguide engineers revealed the existence of such a dataset capturing the ATCO actions.

Ideally, the dataset should contain the following information:

- Sector sequence information, which captures the airspace configuration used at each moment of the day enabling the identification of the operational sectors used.
- ATCO actions including type and absolute time of its execution. This is the core of the input data: the type and time of the developed action, which enables the identification of the ATCO strategy (Section 8.3). The action types are a function of each ACC and its associated working practices.
- Flights associated with the achievement of each ATCO action. As can be seen in Section 8.4 different perceived complexity levels are obtained depending on the
association of ATCO actions to different flights. In other words, a particular action, such as climbing a flight, has a different meaning depending on which flight this action is associated with.

- Flight performance data. Information on aircraft performance including vertical (ascent and descent) and lateral manoeuvring is needed to identify the state of the aircraft in relation to the command cleared by the ATCO.

- Airspace user requests and intent. On some occasions ATCO actions may not reveal a need to perform such an action from an ATC point of view i.e. no-separation task is associated with it, but instead it may reveal a request from the flight e.g. request to cruise at a higher FL. A correct differentiation between the origins of the ATCO actions is ideally needed to increase the accuracy of the methodology.

- Coordination between operational sectors. In the same way as in the previous requirement, some actions may be triggered due to requirements on adjacent operational sectors and not due to ATC requirements in the assessed sector. These differences should be identified.

For the two ACCs analysed during the development of the thesis, the ideal dataset could not be obtained. Data either did not exist or had to be found from other files different from the main data stream containing the ATCO actions. The paragraphs below introduce the MUAC dataset and its associated data processing in order to be used by the methodology, which is transferable to any other dataset.

In the MUAC case the following data could be obtained and were used for the implementation of the methodology in this ACC:

- Sector sequence data (*Sector sequence log*).

- ATCOs actions (*Input log*). Table 8-1 introduces the types of actions and their definitions. The input log includes the following fields apart from the input type (Table 8-2):
  - Time when an action is performed or entered to the ATC system
  - ATCO role: either EC or PC
  - The aircraft associated CS
  - ADEP and ADES associated with each flight
An additional text field (data field) including complimentary information to the action e.g. magnitude of a cleared heading.

Table 8-1 MUAC input types and definition

<table>
<thead>
<tr>
<th>Input type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assume flight (ASM)</td>
<td>Input made to the system to acknowledge that a flight is now under the control of the ATCO pair</td>
</tr>
<tr>
<td>Cancel assume flight (XASM)</td>
<td>Input made to the system when a flight under the control of the ATCO pair is transferred to the next operational sector</td>
</tr>
<tr>
<td>Direct to point (D2P)</td>
<td>Input made to the system when a flight is cleared to navigate towards a given point in the airspace</td>
</tr>
<tr>
<td>Heading (HDG)</td>
<td>Input made to the system when a flight is cleared to navigate in a defined course</td>
</tr>
<tr>
<td>Speed (SPD)</td>
<td>Input made to the system when the flight is instructed to fly at a defined speed or speed range</td>
</tr>
<tr>
<td>Cleared Flight Level (CFL)</td>
<td>Input made to the system when a flight is instructed to perform an ascent or descent towards a different FL</td>
</tr>
<tr>
<td>Transfer Flight Level (TFL)</td>
<td>Input made to the system when the transfer FL between operational sectors needs to be revised i.e. the new FL is different from the one stated in the LoA</td>
</tr>
</tbody>
</table>

Table 8-2 Input log example

<table>
<thead>
<tr>
<th>Time</th>
<th>Sector</th>
<th>Role</th>
<th>CS</th>
<th>ADEP</th>
<th>ADES</th>
<th>Action</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:16:21</td>
<td>DDH</td>
<td>EC</td>
<td>DLH21</td>
<td>LEPA</td>
<td>EDDM</td>
<td>COORD NFL</td>
<td>360</td>
</tr>
<tr>
<td>08:17:27</td>
<td>DDH</td>
<td>EC</td>
<td>DLH21</td>
<td>LEPA</td>
<td>EDDM</td>
<td>ASM</td>
<td>-</td>
</tr>
<tr>
<td>08:28:32</td>
<td>DDH</td>
<td>EC</td>
<td>DLH21</td>
<td>LEPA</td>
<td>EDDM</td>
<td>CFL</td>
<td>270</td>
</tr>
<tr>
<td>08:31:43</td>
<td>DDH</td>
<td>EC</td>
<td>DLH21</td>
<td>LEPA</td>
<td>EDDM</td>
<td>XASM</td>
<td>-</td>
</tr>
</tbody>
</table>

- Entry and exit FL to operational sectors (Flight level log). This corresponds to the
actual altitude of the flight when it is assumed by a different operational sector and not to the altitude when a flight crosses the geometrical boundaries of the sector. The “assumed” altitude or FL is used as opposed to the “geometrical” altitude or FL in order to capture the reality of the operations in MUAC, since flights are typically not assumed when the geometrical boundaries of operational sectors are crossed.

An example of the *Flight level log* file is shown in Table 8-3.

<table>
<thead>
<tr>
<th>CS</th>
<th>Aircraft</th>
<th>ADEP</th>
<th>ADES</th>
<th>ETI</th>
<th>Entry FL</th>
<th>XTI</th>
<th>Exit FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRA456</td>
<td>B738</td>
<td>GCLP</td>
<td>EHAM</td>
<td>01:48:18</td>
<td>380</td>
<td>01:55:16</td>
<td>360</td>
</tr>
<tr>
<td>UAE222</td>
<td>B77L</td>
<td>KDFW</td>
<td>OMDB</td>
<td>02:12:53</td>
<td>350</td>
<td>02:34:43</td>
<td>350</td>
</tr>
<tr>
<td>VDA4228</td>
<td>IL76</td>
<td>CYMX</td>
<td>EDFH</td>
<td>02:21:56</td>
<td>310</td>
<td>02:41:26</td>
<td>257</td>
</tr>
<tr>
<td>TUI1A</td>
<td>B738</td>
<td>EDDV</td>
<td>GCLP</td>
<td>02:37:22</td>
<td>349</td>
<td>02:52:23</td>
<td>349</td>
</tr>
</tbody>
</table>

**8.2.1 Data pre-processing**

The workload estimation tool does not use directly the raw data from the ATC systems. Data are initially pre-processed and conditioned for the purposes of the methodology. The pre-processing task has two main objectives: unifying variables and terms between different data sources and filtering and converting data into useful information.

Regarding the first objective, different nomenclature is found for the same variables present in different source files. This is the case in time variables and terminology for airspace sectors and airports. The data pre-processing task unifies these variables under a single nomenclature.

Regarding the latter objective, pre-processing filters are applied to ensure that the information provided by the data accurately represents the needs of the methodology. There are four pre-processing filters (Tobaruela et al., 2014b).

- Assignment of inputs to roles

The methodology here developed and applied in the next chapter is tuned to estimate the EC
workload. Therefore, the inputs associated with the EC activity needs to be identified. Even though the ATC system uniquely correlates an input with a role (either EC or PC), in some cases an input theoretically assigned to the EC could be executed by the PC and vice versa.

This tends to happen frequently under very high and very low workload scenarios in order to allow for workload balancing between the ATCOs. For instance, a flight can be commanded a new FL by the EC but the input execution can be performed by the PC to alleviate his workload. In this case, the input is still associated to the EC who is effectively making and communicating the decision of reaching the new FL.

ASM, XASM, D2P, HDG, SPD and CFL are the inputs associated with the EC, whilst TFL is the input associated with the PC.

• Input duplication

A duplicated input is either the replication of the same input by the two ATCOs (EC and PC), which would fall under the category above, or the immediate correction of a command that is overruled by the latest input. The latter case is identified by means of introducing in the methodology a 15 seconds interval after the instruction of each command during which if another input of the same type is executed, it overruns the previous one.

For instance if a flight is cleared to navigate to point A and after 5 seconds it is again commanded to navigate to point B, the former point is removed from the input list and only the latter one would be used for the workload calculations.

This filter allows identifying inputs that correspond to failed instructions or incorrect ATC system use.

• Flight delegation

As discussed in following sections, the presence of flights adds-up in the perceived complexity calculation. However, in dynamic and flexible airspaces such as in MUAC, in some cases it can occur that flights inside the geometric boundaries of an airspace are not effectively being controlled by the ATCO pair associated with the sector. This phenomena is
referred to as flight delegation. A filter is therefore, applied to remove from the calculation of
the workload the flights that have been delegated to other airspaces when they still remain in
the airspace under consideration.

A specific input associated with flight delegation is used in the MUAC ATC system. However, in some cases and to increase ATC system usability, the ATCOs refuse to use this input. They instead delegate a flight by inputting an ASM immediately followed by a XASM. When this sequence is found the methodology associates a flight delegation to the ASM-XASM input pair.

- Training issues

During the observations sessions of ATCOs carried out at MUAC operations room (Section 8.6) it was concluded that the inputs selected by an ATCO reflect the training received. This finding is seen for some of the youngest ATCOs after a flight is assumed. If the assumed flight is going to be cleared to a heading, the ATCO would initially tell the ATC system the exit point of the flight in the sector (D2P input). After this, the heading input would be commanded. Therefore, when a D2P-HDG sequence is identified within a 15 seconds period, the initial D2P is discarded.

8.3 Strategy Identification

As introduced in Section 8.1 the cornerstone of the workload estimation methodology relies on a correct identification of the strategy selected by the ATCO to control the air traffic scenario. Each strategy, which is inferred by a sequence of ATCO actions or inputs is afterwards associated with a perceived complexity and workload level.

The strategy used by the ATCO can be directly identified by means of analysing the ATCO inputs sequence associated with each flight and the relative inputs time. Furthermore, the identification logic can be separately applied in the vertical and lateral dimensions of the flight movement (Tobaruela et al., 2014b).

Figure 8-4 shows an example of two different ATCO strategies in the vertical dimension. In this figure, the ATCO needs to climb a flight from the entry FL to the exit FL (FL 310). In
order to achieve this objective, Figure 8-4 presents two different strategies chosen by the ATCO depending on the characteristics of the air traffic scenario. The first strategy (yellow scenario) represents a direct climb of the flight from the entry to the exit FL, associated with a low complexity air traffic scenario. On the other hand the second strategy (blue scenario) represents a step-climb of the flight with two intermediate FLs (FL 270 and FL 290) before reaching the exit FL (FL 310). The inputs associated with each scenario are captured in Table 8-4.

![Figure 8-4 Example of strategy identification in the vertical dimension](image)

<table>
<thead>
<tr>
<th>Yellow scenario</th>
<th>Blue scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASM</td>
<td>ASM</td>
</tr>
<tr>
<td>CFL 310</td>
<td>CFL 270</td>
</tr>
<tr>
<td>XASM</td>
<td>CFL 290</td>
</tr>
<tr>
<td>-</td>
<td>CFL 310</td>
</tr>
<tr>
<td>-</td>
<td>XASM</td>
</tr>
</tbody>
</table>

It is apparent that the blue scenario indicates a more demanding air traffic scenario to be controlled by the ATCO with the presence of intermediate FLs due to the existence of crossing traffic between entry and exit FLs. In fact the yellow scenario corresponds to a conflict-free air traffic scenario where no additional intervention from the ATCO is required.
However in the blue scenario the ATCO intervenes to ensure separation by providing intermediate FLs. The demanding characteristics of the blue scenario are reflected in the inputs sequence (Table 8-4). The presence of two additional CFLs in the blue scenario for intermediate FLs is computed as additional perceived complexity (Section 8.4).

Figure 8-5 depicts an example formed of two scenarios for the strategy identification in the horizontal dimension. In this figure the ATCO has to clear a flight from the entry point in the sector to the exit point in the sector (point XYZ). In order to achieve this objective two scenarios are presented: the yellow scenario representing a conflict-free scenario and the blue scenario that requires ATCO intervention to ensure separation. The inputs associated with each of the scenarios are shown in Table 8-5.

![Figure 8-5 Example of strategy identification in the lateral dimension](image)

<table>
<thead>
<tr>
<th>Yellow scenario</th>
<th>Blue scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASM</td>
<td>ASM</td>
</tr>
<tr>
<td>D2P XYZ</td>
<td>HDG 090</td>
</tr>
<tr>
<td>XASM</td>
<td>D2P XYZ</td>
</tr>
<tr>
<td>-</td>
<td>XASM</td>
</tr>
</tbody>
</table>

It is obvious that the strategy chosen in the blue scenario indicates a more demanding air
traffic scenario than the yellow scenario. In fact in the blue scenario the ATCO initially clears the pilot to navigate to a course (HDG 090) until potential conflict traffic has crossed and the flight can resume navigation towards the exit point D2P.

The more demanding strategy in the blue scenario is easily identified looking at the input sequence in Table 8-5. The additional HDG 090 input is computed as additional perceived complexity in Section 8.4.

It can be observed from the two examples in Figure 8-4 and Figure 8-5 that the sequence of ATCO inputs to individual flights is an indicator of the strategy chosen by the ATCO to control the air traffic scenario. Based on the type of input and its relative execution time within the overall input sequence for each flight the strategy chosen by the ATCO can be uniquely associated with a perceived complexity value (Tobaruela et al., 2014b). The calculation of the perceived complexity is introduced in the following section.

8.4 Perceived Complexity Calculation

The observation of the inputs sequence associated with each flight under the control of the ATCO pair indicates the strategy chosen by the ATCO. However, this observation only provides a qualitative indication of the ATCO strategy. For instance in the examples provided in the previous section the yellow scenarios represented conflict-free strategies whilst the blue scenarios indicated increasingly demanding scenarios. This poses significant deficiencies in accurately estimating ATCO workload (Section 8.1).

Therefore, the methodology quantitatively infers the perceived complexity level associated with the selection of each strategy under the air traffic scenario conditions through the approach introduced in the paragraphs below.

The approach used is similar to the one used by RAMS FTS (Section 4.2.1). In this FTS tool ATCO workload is calculated adding up the associated workload of the events triggered by the ATC simulator (ISA Software, 2011). For instance, the event of a flight entering an airspace sector has a low workload associated (quantified by a number or weight), whilst a conflict resolution task has a higher workload (quantified by a different number or weight).
These events and their associated workload weights are associated with a period of time. For instance, the event of a flight entering an airspace sector can be creating the workload indicated by its weight during a time period of two minutes since the actual flight entry to the sector.

Similarly, the methodology developed in this thesis makes an identification of ATC events, in this case ATCO inputs, associates a perceived complexity value to each of the inputs and extends their values over certain periods of time (Tobaruela et al., 2014b).

In comparison to the RAMS approach, in the methodology developed in this chapter the perceived complexity value associated with the ATCO inputs is not fixed and depends on the particular ATCO strategy. For instance, in the section below the perceived complexity of the first CFL in the yellow and the blue examples differ, since in the former scenario the CFL is associated with navigating the flight according to the flight plan and in the latter scenario the CFL is executed to ensure separation.

This proves the importance of correctly identifying the ATCO strategy in selecting weights and time durations associated for each of the inputs in the ATCO inputs sequence. The three variables (weight, start time and end time) that characterise the perceived complexity associated with each input are captured by the complexity vector (Tobaruela et al., 2014b) [8-1].

\[
\text{Complexity Vector} = [\text{Weight, Start Time, End Time}] \quad [8-1]
\]

The first dimension (weight) of the complexity vector quantifies the perceived complexity value associated with the input. The weight values are assigned in a 1-4 scale, ranging from low (1), medium-low (2), medium-high (3) and high (4) (Tobaruela et al., 2014b). A 4 points scale is used to ease the calibration process carried out by SMEs (ATCOS), which is further described in Section 8.6. Larger scales were found to be inappropriate by SMEs to quantitatively rank the perceived complexity associated with each of the inputs in the flight inputs sequence.

The second and third dimensions, start and end time respectively, represent the period of time during which the perceived complexity associated with the input is used for the perceived
complexity calculations. During the time-frame before the start time or after the end time, the weight associated with the input corresponds to zero.

After the strategy selected by the ATCO to control each flight has been identified and each of the inputs associated with these flights have been associated to a single complexity vector, formed of a weight a start time and an end time, the total perceived complexity is calculated as a function of time. One-minute slices are selected for the estimation tool implementation (CHAPTER 9), although different durations can be chosen depending on the specific needs of the analysis.

The total perceived complexity calculation is calculated as shown in [8-2]:

$$P_{\text{erceived Complexity}}_{time} = \sum_{i} \text{complexity vector}_{flight \ i}$$  \[8-2\]

In summary, each of the strategies chosen by the ATCO triggers different complexity vectors, which are added up throughout the assessment period. These complexity vectors are triggered by a number of logical rules that associate the inputs sequence with a concrete strategy and its associated complexity vectors. These rules are introduced in the sections below.

8.4.1 Occupancy rule

A flight is within the ATCO pair’s responsibility from the moment it calls into the frequency and it is accepted (ASM input) until the moment the flight is cleared to contact the next sector (XASM).

This rule is associated with an increase of the perceived complexity level due to the number of aircraft under the control of the ATCOs pair. As discussed in Section 3.4.1, occupancy is the main complexity source and it must be captured within the workload estimation methodology. On the other hand, high occupancy levels do not necessarily lead to high complexity. Therefore, other rules are needed to accurately capture perceived complexity drivers.
8.4.2 Heading and Direct-to-Point rules

HDG and D2P inputs are computed together under the same rule since they are coupled inputs. In fact, a flight cannot be cleared to navigate towards a given point (D2P) at the same time as being instructed to maintain a given course (HDG). This coupling effect is unique between these two inputs and does not occur between any other inputs pair. Therefore, the complexity vector associated to a D2P clearance depends on the rest of D2P clearances and the rest of HDG clearances.

The complexity vector associated with each HDG or D2P input depends on its absolute position within all the inputs associated with a single flight. Even though the final rules resulting from the calibration of the methodology for MUAC DECO sectors group is shown in Section 8.6.3, there are three types of complexity vectors depending on the position of the input:

- Prior to initial HDG or D2P input
- Intermediate D2P or HDG input
- Final D2P or HDG input

The reason for this distinction is that intermediate inputs are used to ensure separation and are not the final inputs or the final objective of the ATCO as reflected in the flight plan. Therefore, intermediate inputs are associated with higher levels of perceived complexity (Section 8.6.3).

The final input corresponds to the objective of the ATCO as reflected in the flight plan and is associated with a conflict-free environment and low perceived complexity values.

Finally, before the initial input is executed there is a complexity vector associated with the perceived complexity of either remembering to clear the traffic to the planned HDG or D2P while waiting for crossing traffic to pass and leading to a conflict-free trajectory.

8.4.3 Speed rule

Although the SPD command is applied to the horizontal manoeuvre of the flight as the HDG
and D2P inputs, the SPD clearance is not coupled with the other two and can be applied in combination with them.

In en-route environments the SPD command is not instructed very frequently since the ATCOs prefer other commands to ensure separation, mainly D2P and CFL clearances. However, the SPD command may be used under complex scenarios. This rule captures the associated perceived complexity with the SPD clearance.

In general, distinction can be made between two types of SPD instructions: one associated with the change of the aircraft own speed and another associated with resuming the preferred aircraft own speed.

8.4.4 Cleared Flight Level rules

The CFL rules are independent from the horizontal dimension rules (HDG, D2P and SPD) and the occupancy rule. In fact the CFL rules are associated with the vertical movement of aircraft.

The application of these rules require identifying the actual state of the aircraft in its vertical movement: either level flight, ascending or descending. Based on the data set introduced in Section 8.2, these data are not available. In general, data associated with aircraft performance is not necessarily handled by the ATCO/machine interface system. Therefore, the methodology estimates the aircraft vertical performance based on available data as described below.

The vertical flight state estimation consists in computing an approximate level time (Tobaruela et al., 2014b). The level time is defined as the time when a flight finishes the ascent or descent movement and transitions to a level flight. Each computed level flight is uniquely associated to a CFL input.

Equation [8-3] details the calculation of the level time:

\[
level \ time = (\text{cleared FL} - \text{current FL}) \times 60/15
\]

[8-3]

In this calculation the vertical speed is assumed to be constant and equal to 1500 feet per
minute. This value was found by the three ATCOs participating in the calibration process as a representative indicator of vertical movements in MUAC airspace.

After a flight has been instructed a CFL and this flight has finished the climb or descent as computed by the level time, the perceived complexity associated with the vertical manoeuvre ends, Therefore, the level time is closely related to the end time dimension of the complexity vector as it can be seen in Section 8.6.3.

In the case of a new CFL clearance instructed before the flight has reached its level time, this calculation would have no implication on the complexity vector and its end time would correspond to the time when the following CFL would be instructed.

Following the same logic as in the HDG/DSP rules each input has a complexity vector associated with it depending on the position of the CFL input in the sector sequence:

- Prior to initial CFL
- Intermediate CFL
- Following final CFL

The reason for this is that intermediate CFLs indicate FLs that have been cleared due to passing traffic or impossibility of just clearing the optimal clearance. Therefore, they are associated with high perceived complexity.

The final CFL is related to low perceived complexity as it is associated with the final and conflict-free CFL input. The initial CFL has a perceived complexity associated with the effort of remembering to clear the instruction for a flight after traffic has passed. However, a further break-down is accomplished that distinguishes between ascending and descending traffic.

In fact, during descents the time when the CFL is cleared is not necessarily associated with waiting time until conflicting traffic has passed, but to the time when a flight reaches its TOD (Section 8.6.3).

The study of the inputs sequence performed by the ATCO to each of the flights under control enables the identification of a controlling strategy that is associated to a perceived complexity
level through the use of logical rules and their associated complexity vectors. This process results in a computed perceived complexity figure over time. This perceived complexity figure is associated to a qualitative workload level as explained in the next section.

8.5 **Mental Workload Estimation**

So far this chapter has discussed the theoretical background to the workload estimation methodology, its associated data requirements and pre-processing needs, the strategy identification based on ATCO inputs and the mathematical calculation of a perceived complexity value as a function of time. In addition, the computed perceived complexity value is uniquely associated with a qualitative workload level (Tobaruela et al., 2014b).

The qualitative workload level is selected from a 6-point Likert-type (Likert, 1932) workload scale. These scales are broadly used in general behavioural research including workload analysis studies (Lee and Prevot, 2012, Stein, 1985).

Each numeric value is associated to a workload level in the 6-level workload scale according to the relationships established in Table 8-6.

<table>
<thead>
<tr>
<th>Perceived Complexity</th>
<th>Workload level</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;80</td>
<td>Overload</td>
</tr>
<tr>
<td>70-80</td>
<td>Very high</td>
</tr>
<tr>
<td>60-70</td>
<td>High</td>
</tr>
<tr>
<td>40-60</td>
<td>Medium</td>
</tr>
<tr>
<td>20-40</td>
<td>Low</td>
</tr>
<tr>
<td>&lt;20</td>
<td>Very low</td>
</tr>
</tbody>
</table>

This relationship between the computed perceived complexity and the mental workload level is drawn during the calibration of the workload estimation methodology (Section 8.6). During this process 3 ATCOs were asked to associate different perceived complexity values to one of the levels in the workload scale. No more ATCOs were required for this process as results
were already conclusive.

Each of the levels in the workload scale has an associated characteristic. Very low workload level occurs under low objective complexity air traffic scenario with the ATCO strategically performing its actions with no reactiveness (Section 2.3.6.1). The low workload level is characterised as well by low objective complexity and strategic performance of actions, although some of them can be less strategic and more tactical.

A medium workload level corresponds to a medium complexity scenario where actions are accomplished both tactically and strategically. After this the ATCO effort starts to become noticeable, which in ATC jargon is known as starting to be “busy”. In the high workload level the air traffic scenario complexity is high and most of the actions are tactically accomplished, with some actions becoming reactive. This reactivity becomes more apparent at the very high workload level, when the ATCO operates almost at full capacity. An overload corresponds to a level where the ATCO would have needed additional assistance.

The next section explains how the different parameters of the methodology are calibrated to obtain accurate workload results.

8.6 Calibration

The objective of the calibration process is to accurately identify ATCO working strategies and represent them accurately by the three parameters of the complexity vectors: weight, start time and end time. In this section the calibration process is explained and applied to the MUAC DECO sector group.

The calibration process consists of two separate phases, observations and discussions, and workload reconstruction interviews (Tobaruela et al., 2014b). The aim of the first stage is to develop an initial set of parameters and identification of strategies that is later refined by latter stage. These two phases are described in the two following sections.
8.6.1 Observations and discussions

An initial calibration of the methodology was developed by the author based on 30 hours of observation of ATCOs working in the operational positions corresponding to the MUAC sector group operational sectors. 30 hours were considered a sufficient amount of time, as it enabled the author to capture the differences between air traffic scenarios, differences between individual ATCOs and general working practices and strategies.

During the observations the author sat between the EC and the PC to capture the conversations between the ATCO pair. The author watched the EC radar display and his/her actions on the traffic directly on this display and hearing at the ATCO/pilot radio-frequency. In addition, a supplementary PC coordination telephone, used for coordination between adjacent sectors, was provided to the author in case he wanted to verify the PC coordination process.

During these observations, the author was authorized to speak with both members of the ATCO pair. This enabled hands-on explanations on working procedures and strategies.

After operations the findings of each observation were complemented with 5-minute non-structured discussions. The aim of these discussions was to further clarify any action that was not clearly identified by the author during operations. In addition, the ATCOs were encouraged to provide feedback on the methodology overall.

8.6.2 Workload reconstruction interviews

The initial set of the developed complexity vectors was further refined through expert-based workload qualitative ratings in the workload reconstruction interview stage. The workload reconstruction interviews flow is depicted in Figure 8-6.
Three ATCOs were used in this stage each of them going through the same three 30-minute real traffic replay. The air traffic scenarios replays were selected from those containing a combination of the three following features during its 30-minute duration:

- High occupancy - high complexity
- High occupancy - low complexity
- Low occupancy - high complexity

Seven scenarios were identified by the three ATCOs during a one-month period previous to the accomplishment of the calibration task. Air traffic scenarios with the combination of features described above were easily obtained as this scenario identification task was developed during September 2013. During this time, traffic is typically very high and complex and busy situations occur frequently.

The replays consisted of voice and radar replays of the scenarios selected by the three ATCOs. The replays were shown individually to one ATCO at a time and they were presented as well with the computed perceived complexity curve of the selected scenario and its associated mental workload curve. ATCOs were asked to verify in one-minute intervals if the perceived complexity and workload level corresponded to the workload perception of the ATCO during the replay.

The replay of the air traffic scenario was paused when the ATCO or the author considered worth investigating any specific air traffic situation. During these stops a discussion was held between the ATCO and the author where the former identified the workload level as
compared to the one obtained by the methodology based on the initial calibration performed by the author.

In order to support the development of these discussions the ATCO was provided a break-down of the methodology performance during the period of interest (Table 8-7). The break-downs identified the main sources of perceived complexity computed by the methodology.

Table 8-7 Example of methodology break-down

<table>
<thead>
<tr>
<th>CallSign</th>
<th>'ComplexityFactor'</th>
<th>'ComplexityValue'</th>
<th>'StartPeriod'</th>
<th>'EndPeriod'</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAW33S</td>
<td>CI_ASM</td>
<td>1</td>
<td>17:03:41</td>
<td>17:23:15</td>
</tr>
<tr>
<td>CPA05E</td>
<td>CI_ASM</td>
<td>1</td>
<td>17:26:00</td>
<td>17:42:19</td>
</tr>
<tr>
<td>CPA05E</td>
<td>CI_HDGb</td>
<td>4</td>
<td>17:26:04</td>
<td>17:30:32</td>
</tr>
<tr>
<td>CPA05E</td>
<td>CI_D2Pb</td>
<td>2</td>
<td>18:26:00</td>
<td>17:26:04</td>
</tr>
<tr>
<td>CPA05E</td>
<td>CI_CFLe</td>
<td>1</td>
<td>17:26:00</td>
<td>17:40:32</td>
</tr>
<tr>
<td>DNM356</td>
<td>CI_ASM</td>
<td>1</td>
<td>17:14:35</td>
<td>17:26:29</td>
</tr>
<tr>
<td>DNM356</td>
<td>CI_CFLg</td>
<td>2</td>
<td>17:14:35</td>
<td>17:23:30</td>
</tr>
</tbody>
</table>

In case of a discrepancy between the ATCO and the output of the methodology, the following discussion triggered one or several of the following actions:

- Creation of new strategy.
- Revision of already existing strategy.
- Revision of a complexity vectors.
- Creation of new data pre-processing filter
- Refinement of the data pre-processing filter.

During this calibration stage it was found that the vast majority of the methodology calibration changes were associated with the creation and revision of strategies and fine-tuning of the complexity vectors weights.

In addition ATCOs recognized that during the replay the reconstructed workload was slightly lower than the workload experienced during the actual control of the scenario. This implies that the real control of the traffic creates additional stress and is noted during the validation of
the methodology in the next chapter.

The next sections show the result of the calibration of the workload estimation methodology for the MUAC DECO sectors group.

### 8.6.3 MUAC DECO sectors group calibration results

The two-step calibration approach is used to calibrate the rules and perceived complexity vectors associated with the different inputs type for the MUAC DECO sectors group. In fact, the working procedures and associated complexity of different airspaces differ, resulting in different workload relationships (Flynn et al., 2006).

From the three sectors group available in MUAC (Brussels, DECO and Hannover), the DECO sectors group was selected for the calibration of the methodology as it was found that it presented the highest levels of consistency between the ATCOs working in its sectors.

In addition, ATCOs in DECO use in general the ATC system according to standard procedures. Therefore, data can be used without significant variations in the meanings of the inputs. In other sectors, especially Brussels sectors group, the inputs commanded to the traffic are not usually transmitted to the ATC system. This results in incomplete data sources that can lead to biased results.

Therefore the selection of the DECO sectors group allows to show the potential of the methodology, which could otherwise be lowered by other external factors. The results of the calibration task are captured in Table 8-8 (Tobaruela et al., 2014b) and are explained in the paragraphs below.

The occupancy rule is triggered for aircraft under the control of the ATCO being assessed. During the time period between a flight is assumed by the EC (ASM – start time) until it is transferred to the next sector (XASM – end time), a weight factor of 1 (minimum value in the 1 to 4 weight scale) is assigned to the complexity vector.

The HDG/D2P rules have a more complicated structure, as the relative position of each input in the flight inputs sequence is associated with different complexity vectors. Finally, different
weights are obtained depending on the nature of the input (HDG or D2P).

Prior to the first HDG or D2P input in the flight inputs sector sequence, there is a perceived complexity associated with the waiting time until the input is cleared. Regardless of the input type a weight factor of 2 is obtained from the time the flight is under the responsibility of the ATCO (ASM) until the first HDG or D2P clearance is executed.

Intermediate D2P or HDG inputs show complexity associated with intermediate clearances, which are given as the final clearance cannot be given due to the presence of other traffic (conflicting traffic). A HDG input has an associated weight factor of 3 and D2P of 2. These complexity vectors are extended from the instant the input is cleared (HDG or D2P respectively) until another D2P or HDG input is instructed to the flight.

The last input within the HDG/D2P rules (either HDG or D2P) is associated with the objective input i.e. the one that needs to be cleared to comply with the flight requirements as reflected in the flight plan. Therefore, the last input should have a low perceived complexity associated with it and extends from the instant the last input is cleared until the flight leaves the sector (XASM).

This is the case for a D2P, which is associated with a weight factor of 1. However, a weight factor of 3 is obtained for the HDG case. In fact, a flight leaving the sector flying in a heading course (HDG) instead of navigating towards a point (D2P) represents a non-nominal flight transfer that indicates additional perceived complexity.

The SPD rule is triggered when a flight is instructed to fly at a precise speed or within a given speed range. This complexity vector lasts from the moment the input is executed (SPD) until another SPD input is commanded or the flight is instructed to resume its own speed or the flight exits the sector (XASM). A weight factor of 3 is obtained for the SPD rule as a SPD command indicates high perceived complexity, otherwise the ATCO would not modify the preferred flight speed.

Finally, similar to the HDG/D2P rules, the CFL rules are formed of several complexity vectors depending on the position of the CFL instruction in the overall flight inputs sequence and on the performance of the flight (ascent or descent).
In the case of CFL commands for ascending flights the complexity vectors are differentiated for initial CFL, intermediate and final CFL. In the first case the complexity vector extends from the time the flight is assumed by the ATCO (ASM) until the flight reaches its FL calculated through the level time assumption [8-3] or another CFL input is commanded. A weight factor of 4 is associated with this rule since it is associated with conflicting traffic that prevents from clearing the ideal CFL.

For intermediate CFLs the weight factor continues to be 4 and it is extended from the moment the input is cleared until a new CFL is instructed or the flight reaches a constant level flight attitude.

The last CFL is instructed when the ATCO has ensured that the climb is conflict free and the FL of the flight plan can be finally cleared. This indicates low perceived complexity, hence a weight factor of 1 is obtained. This extends from the moment the final CFL is instructed until the flight is transferred to the next sector (XASM) or the flight reaches the instructed FL, whichever happens first.

In the case of the flight being instructed to descend, the same logic and complexity vector apply for the final CFL inputs. However, some differences arise for the initial and final CFLs. As already introduced in Section 8.4, a late command for descent relative to the time the flight enters a sector (ASM) does not indicate that the flight could not descend due to other traffic. When this occurs it usually indicates the location of the TOD for the flight is after the flight is assumed. Therefore, the initial CFL does not have a high perceived complexity associated with it. In addition if the flight has only one CFL in the inputs sequence, the complexity is lower (weight factor of 1) than in the case of various inputs (weight factor of 2). Both complexity vectors extend from the ASM time until the level time or until the flight exits the sector, whichever comes first.

In the case of the final input, the methodology searches for a TFL input in flight inputs sequence that indicates a negotiation between the current and the next sector of the transfer FL. When a TFL is present, a negotiation has been accomplished indicating higher perceived complexity (weight factor of 4), than when no negotiation is accomplished due to the non-existence of conflicting traffic (weight factor of 1). In both cases, the complexity vector lasts
from the instruction of the CFL until the flight reaches the commanded FL or exits the sector, whichever happens first.
Table 8-8 MUAC DECO sectors group logic rules and complexity vectors calibration

<table>
<thead>
<tr>
<th>Rules</th>
<th>Condition</th>
<th>Weight</th>
<th>Start time</th>
<th>End time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupation</td>
<td>-</td>
<td>1</td>
<td>ASM</td>
<td>XASM</td>
</tr>
<tr>
<td>HDG/D2P</td>
<td>Prior to first input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>If D2P</td>
<td>2</td>
<td>ASM</td>
<td>D2P</td>
</tr>
<tr>
<td></td>
<td>If HDG</td>
<td>2</td>
<td></td>
<td>HDG</td>
</tr>
<tr>
<td>Intermediate inputs</td>
<td>If D2P</td>
<td>2</td>
<td>D2P</td>
<td>Next D2P or HDG</td>
</tr>
<tr>
<td></td>
<td>If HDG</td>
<td>3</td>
<td>HDG</td>
<td></td>
</tr>
<tr>
<td>After last input</td>
<td>If D2P</td>
<td>1</td>
<td>D2P</td>
<td>XASM</td>
</tr>
<tr>
<td></td>
<td>If HDG</td>
<td>3</td>
<td>HDG</td>
<td></td>
</tr>
<tr>
<td>SPD</td>
<td>-</td>
<td>3</td>
<td>SPD</td>
<td>Next SPD or XASM</td>
</tr>
<tr>
<td>CFL</td>
<td>Ascent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prior to first CFL</td>
<td>4</td>
<td>ASM</td>
<td>CFL or time level</td>
</tr>
<tr>
<td></td>
<td>Intermediate CFLs</td>
<td>4</td>
<td>CFL</td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>After last CFL</td>
<td>1</td>
<td>CFL</td>
<td>XASM or time level</td>
</tr>
<tr>
<td>Descent</td>
<td>Prior to first CFL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Only 1 CFL</td>
<td>1</td>
<td>ASM</td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>Several CFLs</td>
<td>2</td>
<td></td>
<td>CFL</td>
</tr>
<tr>
<td>Intermediate CFLs</td>
<td></td>
<td>4</td>
<td>CFL</td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>After last CFL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>With TFL</td>
<td>4</td>
<td>CFL</td>
<td>XASM or time level</td>
</tr>
<tr>
<td></td>
<td>Without TFL</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

334
8.7 Summary

This chapter has developed a novel methodology for estimating ATCO workload during RTS exercises, operational trials and real operations. The methodology uses ATCO inputs to the ATC system as indicators of ATCO workload. Based on its approach, the methodology overcomes the most significant deficiencies of currently existing workload estimation techniques: large post-operations tasks, lack of capturing ATCO individual strategies and ATCO interference during RTS, operational trials or real operations.

The ATCO inputs are assessed by the methodology in order to infer the type of control strategy used by the ATCO. In inferring this strategy the methodology uses the type of input and relative inputs sequence associated with each flight.

Different logical rules are triggered depending on the strategy identification, which enables the calculation of a perceived complexity value for each flight as a function of time. The addition of the individual perceived complexities for all the flights during the evaluation time yields the perceived complexity evolution figure. The perceived complexity values are finally associated with a qualitative workload level in a 6-point scale.

This novel methodology, which uses for the first time ATCO ATC system inputs as workload indicators, has resulted into a patent application (UK Patent Application No. 1405708.7, UK Intellectual Property Office), since some of the most advanced centres in Europe have recognised its potential for application during and after operations.
The objective of this chapter is to validate and apply the workload framework area.

Two ACCs (MUAC and GUAC) are selected for the validation of the methodology in order to demonstrate transferability. However, the validation in GUAC is not terminated due to the lack of technical resources of the ACC and no significant transferability conclusions are achieved.

Section 9.1 develops the structure of the validation process. Sections 9.2 and 9.3 apply the validation strategy to MUAC and GUAC respectively and discuss the results. Finally, Section 9.4 discusses the potential application of the novel workload estimation methodology.

9.1 Validation Strategy

A validation strategy is developed in the current section to demonstrate the accuracy of the workload estimation methodology results. The accuracy of the methodology outputs are...
calculated in relation to workload ratings made by licensed ATCOs.

An alternative validation approach consisting in a comparison to RAMS FTS output was envisaged during the development of the research. This approach has the main advantage of enabling the assessment of the accuracy of the methodology developed in CHAPTER 8 in relation to the RAMS tool outputs.

However, the approach was not implemented. The main reason for this was that in the discussions with SMEs held during the development of the workload estimation method (CHAPTER 8) it was found that the RAMS tool had not been successfully calibrated for the MUAC airspace. The amount of time and ATCO resources required to attempt the calibration of the tool during the PhD time-frame, along with the finding that the MUAC SMEs had previously decided to move away from the tool, led to the decision of using ATCO workload-rating as the main validation methodology.

In order to prove that the methodology accurately estimates ATCO workload during the different conditions of the ATC operations using the ATCO workload-rating approach, the validation tasks should ensure that the following requirements are met:

1. The validation scenarios should be representative of the entire workload spectrum (from low to high). The overload phase is not modelled in the workload estimation methodology (CHAPTER 8), and therefore, it is not a validation objective, although it is necessary to identify the overload transition point i.e. the workload level above which the ATCO workload is considered to be an overload.

2. The validation task should demonstrate the transferability of the workload estimation methodology i.e. its ability to be applied after calibration to different ACCs and airspace sectors regardless of its size, local airspace and working procedures, and ATC systems.

3. The validation task should ensure that the workload estimation methodology is accurate in estimating the ATCO workload for a representative ATCO population sample.

The validation strategy process is depicted in Figure 9-2. This figure shows that the process is formed of six different validation steps (numbered and in dashed quadrangles). These
validation steps are interrelated between them as shown by the connecting arrows. In addition, the output of each of the validation steps is shown in continuous line quadrangles. Finally, externally imposed factors affecting the validation methodology are encircled in Figure 9-2.

Figure 9-2 Validation strategy flow diagram

The sections below discuss each of the validation stages in detail.

9.1.1 Step 1: Validation scenarios identification

The aim of this validation step is to identify real air traffic scenarios that would have potentially generated a workload level sufficient to meet validation requirement 1. Low workload levels are easily identifiable by means of evaluating the air traffic demand. However, high workload states are not always correlated with high air traffic demand scenarios (Section 3.4.1). In addition, medium air traffic demand scenarios can create very
demanding workload conditions.

In summary, the relationship between demand and workload is not unique, as discussed in CHAPTER 3. Therefore, and in order to cover an ATCO workload range from low to high levels, the identification of the workload scenarios is achieved in two different ways:

- Air traffic demand is assessed for low ATCO workload scenarios identification.
- In the case of high ATCO workload scenarios identification, there is a need to measure the workload experienced in real operations. There are two possibilities to accomplish this:
  - ATCO workload ratings during real operations.
  - ATCO workload ratings after operations.

The first option proposed within the identification of high workload scenarios has the potential to be very accurate as opposed to the second option, in which the ATCO relies on his memory (Section 4.2.2).

On the other hand, ATCO self-assessment of workload ratings during normal operations can interfere with the ATCO job, hence ACCs do not allow this approach.

In order to benefit from the advantages of real operations workload assessment (Section 4.2.2), an approach for on-the-job ATCO workload identification is designed. This approach avoids any type of interference with the ATCO job during real operations. In fact, the ATCO is only requested to note down the time, operational sector and operational position, whenever he/she finds that a high workload situation occurred. This approach is similar to the one used by ACCs in developing overload reports.

After the ATCO has finished a shift, the three parameters are communicated to the validation supervisor (in this thesis the author, and finally the air traffic scenario is considered as a potential validation scenario.

This approach is not even necessary for the Skyguide case. This is due to the existence of a workload monitoring tool in GUAC: the CRYSTAL tool (skyguide). The CRYSTAL tool is a workload/complexity estimation tool, calibrated for the GUAC sectors, whose workload
output can be assessed in order to obtain high and low workload real air traffic scenarios.

The result of the validation strategy step 1 is a pool of real air traffic scenarios, which contain several scenarios ranging from low to high workload scenarios and for different airspace sectors.

It has to be noted that the season when the validation of the workload estimation methodology is developed has a crucial impact on the quality of the air traffic scenarios pool. It has been discussed throughout this thesis that air traffic demand is very seasonal, and due to the relationship between air traffic demand and workload, the latter can be seasonal as well.

Therefore, in order to ease the identification of a wide range of air traffic scenarios from low to high workload, summer appears to be the ideal time to conduct this validation strategy step. In fact, during summer it is very typical to see very high workload conditions during peak hours and low workload conditions during less busy times.

This research accomplished this task during Winter 2013 and this implied a difficult identification of high workload scenarios due to the lack of air traffic demand and their associated complex scenarios (Section 9.2).

9.1.2 Step 2: Selection of optimal validation scenarios

The output of validation step 1 is a pool of potential validation scenarios. However, due to staff and time limitations not all of these scenarios can be used for validation. Therefore, step 2 focuses on selecting the optimal validation scenarios, discarding any that has abnormal characteristics.

The abnormal operations include occurrences such as ATC system failure, non-nominal procedures (e.g. military event) and ATCOs not using the ATC system according to the ATC system user manual. This last factor is of crucial importance since an incorrect use of the ATC system could result in the generation of a flawed data set that would finally translate into inaccurate workload results. In addition, it has to be verified that the potential scenarios do meet the ATCO workload validation requirements stated in the validation requirement 1.
In order to accomplish this validation step, the validation supervisor is supported by one ATCO who ensures an optimal selection of validation scenarios. Each potential validation scenario is replayed once (voice + radar) during the scenarios verification.

The result of validation step 2 is a set of validation scenarios selected from the initial validation scenarios pool, which are used in later stages of the methodology to perform the comparison between real ATCO workload ratings and the outputs of the developed workload estimation methodology.

9.1.3 Step 3: Workload estimation

Validation step 2 is partially supported by the outputs of the workload estimation methodology for the initial validation scenarios pool. The potential validation scenarios gathered at the end of validation step 1 are typically 30-minute scenarios. In order to reduce the verification time during the replays check performed by the validation supervisor and the verification ATCO, the estimation methodology outputs are used in this step. These outputs enable narrowing down the crucial period of time of each potential validation scenario i.e. if the methodology computes a workload peak during a certain period of time, the verification will initially be focused on that period of time, ensuring that workload actually reaches the desired levels.

Furthermore, the workload estimation methodology outputs are compared afterwards with the ATCO workload rating results in order to assess the accuracy of the methodology.

9.1.4 Step 4: ATCOs selection

Validation requirement 3 states that the validation should demonstrate that the methodology outputs are representative of the ATCOs population. A representative ATCO population should capture different ATCO subjective factors that can affect performance, which are fundamentally embedded in the ATCO experience or age (Rothaug, 2003, Thackray, 1981).

Therefore, a dedicated ATCO selection process is needed to comply with validation
requirement 3. However, this selection is limited by staffing availability. In fact, the ATCOs used for validation purposes are usually employed during labour-paid times. The demography of the working ATCOs during a normal day, is not designed according to ageing distributions, hence the days when the validation are carried out it may occur that the ATCOs do not optimally represent the complete ATCO population.

Taking into account this limitation the ATCOs validation team should be designed to be as most representative of the ATCO ACC population as possible, given the staffing constraints.

The result of this validation step is the creation of a validation team that consists of a number of ATCOs that rate the workload for the chosen validation scenarios. The workload ratings produced by the validation team are finally compared against the methodology outputs in order to assess its accuracy.

**9.1.5 Step 5: Workload reconstruction**

The aim of this validation step is to obtain a reconstruction of the workload experienced by the ATCOs during each of the validation scenarios. Workload ratings are obtained after operations using replays (radar + voice) of the validation scenarios. The ATCOs belonging to the validation team are in charge of rating the workload that the ATCO actually controlling the traffic during operations was experiencing (Tobaruela et al., 2014b). This implies that the ATCOs participating in the workload reconstruction step are not asked to rate the scenario workload just considering the complexity of the scenario but also taking into account the performance of the operating ATCO.

For instance, if during the replay it is observed that the operating ATCO is conducting incorrect actions e.g. incorrect CFL, which could be due to high levels of perceived complexity, the validation ATCO should reflect this performance as an increased workload level, even if the objective scenario complexity should have not generated high workload levels.

All the ATCOs in the validation team reconstruct the workload for each of the scenarios. The results of the workload ratings for each scenario and each ATCO are subsequently analysed in validation step 6 in order to define the actual scenario workload.
The workload reconstruction step is organized in sessions in which a maximum of two ATCOs participate at the same time. Sessions are designed to have a duration of 3 hours in accordance with the MUAC roster office staff requirements. In addition, in order to meet further staff availability requirements, sessions can eventually be split into 2 separate parts. In this case, the session break is suppressed and the two resulting sub-sessions are formed of the pre-break tasks and the post-break tasks respectively. The workload reconstruction sessions are organized as depicted in Figure 9-3.

![Figure 9-3 Validation session flow (time in minutes)](image)

As seen in Figure 9-3 a validation session consists of three fundamental parts: session briefing, scenarios replays started with an individual scenario briefing and the final session debriefing. An intermediate session break is placed in the middle of the session to allow ATCOs to rest for a period of 5-10 minutes. Each of these parts is described in the following sub-sections.

### 9.1.5.1 Sub-step 5.1: Session briefing

A session briefing is needed to introduce each of the members of the validation team to the validation tasks, especially the workload reconstruction step. As the validation ATCOs are not involved in the development of either the workload model or the identification of validation scenarios, a briefing session is designed to prepare them for the process. The session briefing is performed by the validation supervisor and consists of the following key areas:

- General overview of the workload estimation methodology and the need for a validation task.
• Introduction of the tasks that the ATCOs are required to accomplish during the validation session. Special emphasis is placed on two crucial validation items:
  ○ Correct understanding of the workload reconstruction scale i.e. understanding what each level represents. In fact, ATCOs participate in different validation tasks within the projects that are carried out in the ACCs. Therefore, ATCOs may be used to different workload scales and to estimate their workload in different environments e.g. during FTS exercises. However, the validation of this workload methodology is performed in quite a novel way (using scenario replays), and is of fundamental importance that the validation ATCOs understand the validation methodology employed and particularly the workload scale.
  ○ Correct differentiation between scenario complexity or potential scenario workload and actual workload experienced by the ATCO.
• Validation-booklet hand-out (see Appendix 6). The validation-booklet gathers all the information conveyed during the session briefing and each of the individual validation scenario session briefings. The ATCOs can look up any information during the development of the workload reconstruction validation step. The validation-booklet contains the following information:
  ○ Highlights of the key points discussed during the session briefing.
  ○ Validation scenarios definition.
  ○ Questionnaire for session debriefing (Section 9.1.5.4).

9.1.5.2 Sub-step 5.2: Individual validation scenario briefing

During the workload reconstruction validation step and before the start of each validation replay, the validation supervisor briefs the ATCOs on the characteristics of the next air traffic scenario replay. This individual briefing lasts approximately five minutes and is conducted six times during the workload reconstruction step, one for each validation scenario.

The most important points of the individual scenario briefing are captured in the validation booklet and include:

• Date and time of the validation scenario.
- Operational sector of the validation scenario including previous airspace configuration or any airspace configuration changes in adjacent sectors during the duration of the validation scenario.

Finally, before the scenario replay is started the initial scenario replay frame is frozen for approximately a minute in order to allow the validation ATCOs time to build a mental picture and identify the scenario characteristics. Following this, the next sub-step is initiated.

9.1.5.3 Sub-step 5.3: Validation scenario replay and workload reconstruction

During the validation scenario replay the validation ATCOs are expected to reconstruct the workload experienced by the ATCO who actually operated that scenario. An exact radar screen replay along with a reproduction of the radio-frequency transmitted is presented to the validation ATCOs. This is shown in a display with the same dimensions as the actual ATC displays, in order to avoid image distortions or ATCO lack of familiarity issues (Figure 9-4). In the case of 2 ATCOs participating in the same session a physical barrier is placed between 2 ATCOs to avoid them seeing the workload values of the other ATCO. Therefore, each ATCO workload reconstruction can be assumed to be independent from the rest of the results of the other validation ATCOs.
Workload is rated by the ATCOs in one-minute intervals, which are the same intervals produced by the workload estimation methodology. The reconstruction task is carried out with the use of a workload assessment tablet, which replaces the old workload assessment keyboards (Kopardekar et al., 2008b). Through the use of the workload assessment tablets the ATCOs ratings can be digitally stored for further post-processing. The workload assessment tablets have been equipped with software configured to prompt a workload scale every one-minute (Figure 9-5). The ATCO presses a workload level every time the scale is prompted.
The workload scale used for the workload reconstruction validation step is developed in CHAPTER 8 and consists of the levels shown in Table 9-1:

Table 9-1 Workload levels and associated definitions

<table>
<thead>
<tr>
<th>Level</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overload</td>
<td>Assistance is needed</td>
</tr>
<tr>
<td>Very High</td>
<td>Scenario complexity is high and actions are both tactically and reactively accomplished</td>
</tr>
<tr>
<td>High</td>
<td>Scenario complexity is high and most actions are tactically accomplished, others are reactively accomplished</td>
</tr>
<tr>
<td>Medium</td>
<td>Scenario complexity is medium actions are both tactically and strategically (pre-planning) accomplished</td>
</tr>
<tr>
<td>Low</td>
<td>Scenario complexity is low and most actions are strategically accomplished (pre-planning), others are tactically accomplished</td>
</tr>
<tr>
<td>Very Low</td>
<td>Scenario complexity is low and actions are strategically (pre-planning) accomplished</td>
</tr>
</tbody>
</table>
The exact definition of each workload level in Table 9-1 is performed with one ATCO not participating in the validation tasks and with experience in other validation tasks activities. This ensures that validation ATCOs will understand the workload scale.

9.1.5.4 Sub-step 5.4: Session debriefing

The session debriefing is accomplished through a questionnaire and an unstructured discussion. In the case of 2 ATCOs, the debrief is done at the same time, ensuring that ATCOs do not discuss results before completing the questionnaire. This is done immediately after the last validation scenario replay is finished.

The debriefing aims to capture the degree of comfort of the validation ATCO with the validation session in order to capture any potential factors that might negatively influence in the accuracy of the workload ratings.

In the questionnaire the ATCOs show their points of view in respect to a list of statements:

- Statement a: The scenario briefing information is sufficient
- Statement b: The validation scenarios are representative of usual operations
- Statement c: I felt capable of reconstructing the workload
- Statement d: I felt comfortable with the scenarios duration
- Statement e: I consider the workload scale to be appropriate

A four-point Likert-Type scale from 1 (strongly disagree) to 4 (strongly agree) is used in order to state the conformance of each of the ATCOs to the statements above (Appendix 6).

9.1.6 Step 6: Deviation analysis

The aim of this step is to compare the results of the workload reconstruction interviews with the outputs of the workload estimation methodology. This statistical analysis should determine to which extent and under which conditions the workload methodology has proven to be accurate and therefore is validated.
9.2 MUAC Validation

The validation strategy (Figure 9-2) developed in the previous section is applied to MUAC and in particular to the DECO sectors group.

In order to achieve validation step 1 (validation scenarios identification) all the ATCOs operating at the MUAC DECO sectors group are informed of the identification task. MUAC uses an electronic tool (eBrief) to automatically communicate important information to ATCOs regarding new procedures or special events. Furthermore, other non-critical information from an operational point of view can be displayed in the eBrief tool.

The requirement for the ATCOs to identify validation scenarios was shown in the non-critical part of the eBrief tool to the MUAC DECO sectors ATCOs. At the end of step 1 a total of 14 potential validation scenarios were identified to form the initial validation scenarios pool.

From the initial 14 potential validation scenarios pool, 6 were selected in step 2 (selection of optimal validation scenarios) as optimal validation scenarios. The total number (6) of optimal validation scenarios is chosen according to ATCOs staff limitations. Since each of the ATCOs in the validation team should reconstruct the workload for each of the validation scenarios and each additional scenario adds up approximately 30 minutes (Figure 9-3) to the workload reconstruction step, 6 scenarios is the maximum number of validation scenarios within the 180 minutes MUAC roster office constraint.

The validation scenarios (Appendix 6) were selected to represent the widest range of representative operational scenarios in the MUAC DECO sectors group. The final validation scenarios are gathered in Table 9-2.
Table 9-2 Validation scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Operational sector</th>
<th>Active ATCO</th>
<th>Date</th>
<th>Start time</th>
<th>End time</th>
<th>Total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jever + Holstein</td>
<td>VV</td>
<td>18/10/13</td>
<td>11:40</td>
<td>12:00</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Jever</td>
<td>NR</td>
<td>21/10/13</td>
<td>08:45</td>
<td>09:05</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>Delta High</td>
<td>VV</td>
<td>18/10/13</td>
<td>08:50</td>
<td>09:10</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Delta High</td>
<td>VJ</td>
<td>24/10/13</td>
<td>10:00</td>
<td>10:20</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>Delta</td>
<td>FM</td>
<td>31/10/13</td>
<td>20:40</td>
<td>21:00</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>Delta</td>
<td>WS</td>
<td>07/11/13</td>
<td>07:40</td>
<td>08:00</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 9-3 describes in more detail the characteristics of each of the six validation scenarios, with special emphasis on the workload range and the air traffic demand of the operational scenario.

Table 9-3 Validation scenarios characterization

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTMV</td>
<td>18/21</td>
<td>18/21</td>
<td>18/21</td>
<td>18/21</td>
<td>18/21</td>
<td>18/21</td>
</tr>
<tr>
<td>Max occupancy during the scenario</td>
<td>24</td>
<td>26</td>
<td>23</td>
<td>21</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>Minimum occupancy during the scenario</td>
<td>12</td>
<td>16</td>
<td>8</td>
<td>14</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Max/min difference during the scenario</td>
<td>12</td>
<td>10</td>
<td>15</td>
<td>7</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Maximum computed perceived complexity</td>
<td>66 (High)</td>
<td>77 (Very high)</td>
<td>55 (Medium)</td>
<td>51 (Medium)</td>
<td>71 (Very high)</td>
<td>61 (High)</td>
</tr>
<tr>
<td>Minimum computed perceived complexity</td>
<td>29 (Low)</td>
<td>42 (Medium)</td>
<td>14 (Very low)</td>
<td>30 (Low)</td>
<td>38 (Low)</td>
<td>25 (Low)</td>
</tr>
<tr>
<td>Max/min computed perceived complexity difference</td>
<td>37</td>
<td>35</td>
<td>41</td>
<td>19</td>
<td>33</td>
<td>36</td>
</tr>
</tbody>
</table>

As seen from Table 9-3 the six validation scenarios have a wide range of computed perceived complexity.
complexity, which in turn indicate a wide actual workload range. This is line with the expectation as requested of the ATCOs during the validation scenarios identification step. Occupancy is typically very high, with 4 out of the 6 validation scenarios showing an excess of air traffic demand according to the OTMV values.

The validation step 4 (ATCOs selection) is accomplished complying with MUAC roster office limitations. The ATCOs belonging to the validation team are assigned by the MUAC roster office based on an air traffic demand / ATCOs availability assessment. Spare ATCOs according to MUAC staffing office are assigned to the validation team. A total number of 8 ATCOs are used for the validation task.

Table 9-4 shows the characteristics of the ATCOs validation team assigned by the MUAC roster office. In this table the focus is to analyse the demographics of the validation team (age, gender and experience). In addition, other variables such as their participation in other validation projects within MUAC (side track), licenses in other sectors and their ATCO category (belonging to the MUAC EOS team), is captured in this table. Finally, it is indicated whether each of the ATCOs had reported or worked on any of the validation scenarios.

<table>
<thead>
<tr>
<th>ATCO</th>
<th>XX</th>
<th>BW</th>
<th>CM</th>
<th>KV</th>
<th>BQ</th>
<th>RP</th>
<th>BD</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>29</td>
<td>33</td>
<td>41</td>
<td>51</td>
<td>39</td>
<td>39</td>
<td>41</td>
<td>34</td>
</tr>
<tr>
<td>Gender</td>
<td>Male</td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Male</td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
</tr>
<tr>
<td>Side Track</td>
<td>No</td>
<td>No</td>
<td>CWG</td>
<td>No</td>
<td>No</td>
<td>CWG</td>
<td>CWG</td>
<td>SMART</td>
</tr>
<tr>
<td>Other licenses</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>EOS</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Scenario reporter</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Worked any scenario</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

The average age of the validation team is 38.4 years with a standard deviation of 6.65 years.
The average experience is 9.33 years with a standard deviation of 6.04 years. Out of the 8 ATCOs, 2 were women and 6 men. Half belonged to ATCO groups who perform validation activities, hence it could be assumed that the validation activities would be more straightforward due to their familiarity with the process. However, only one of them reported a scenario, which indicated a low involvement in the previous steps of the validation process. Finally, none of the ATCOs had previously worked on any of the scenarios, which prevented obtaining biased results due to previous knowledge.

Validation step 5 (workload reconstruction) is accomplished according to Section 9.1.5 guidelines. Sessions were carried out with one or two ATCOs depending on the validation team availability.

Table 9-5 shows the proportion of ATCOs workload level ratings relative to the total responses. Figure 9-6 shows the frequency of responses for all the validation scenarios combined per workload level for each of the ATCOs (two-letter code representing each of the validation ATCOs).

The table and figure represent one of the crucial issues in determining the actual workload level resulting from the ratings of the validation ATCOs: the variance of their responses. The mode of the workload level responses for all the ATCOs is medium, except for VI and BW ATCOs, who show a mode of low workload. This confirms the importance of the ATCO subjectivity in ATC and its relationship to workload.
Table 9-5 Percentage of workload level responses

<table>
<thead>
<tr>
<th>ATCO</th>
<th>Very Low</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>XX</td>
<td>2.5%</td>
<td>31.67%</td>
<td>43.33%</td>
<td>19.17%</td>
<td>3.33%</td>
</tr>
<tr>
<td>VI</td>
<td>2.5%</td>
<td>47.5%</td>
<td>35.83%</td>
<td>14.17%</td>
<td>0%</td>
</tr>
<tr>
<td>RP</td>
<td>0%</td>
<td>16.67%</td>
<td>61.67%</td>
<td>21.67%</td>
<td>0%</td>
</tr>
<tr>
<td>KV</td>
<td>0%</td>
<td>12.5%</td>
<td>46.67%</td>
<td>25%</td>
<td>15.83%</td>
</tr>
<tr>
<td>CM</td>
<td>0%</td>
<td>8.33%</td>
<td>44.17%</td>
<td>40%</td>
<td>7.5%</td>
</tr>
<tr>
<td>BW</td>
<td>1.67%</td>
<td>35%</td>
<td>26.67%</td>
<td>30.83%</td>
<td>5.83%</td>
</tr>
<tr>
<td>BQ</td>
<td>0%</td>
<td>8.33%</td>
<td>55.83%</td>
<td>25%</td>
<td>10.83%</td>
</tr>
<tr>
<td>BD</td>
<td>0%</td>
<td>5.83%</td>
<td>55%</td>
<td>34.17%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Figure 9-6 Frequency of responses per workload level and ATCO

The low levels of agreement between the ATCOs ratings has a significant impact on the validation results as discussed in the next section.

9.2.1 Deviation analysis

Table 9-6 to Table 9-11 show the results of workload reconstruction ratings and the outputs of the workload estimation methodology for the different validation scenarios. The former is presented in the upper table where the frequency of workload level responses (VH-Very

353
High; H-High; M-Medium; L-Low and VL-Very Low) for each one-minute interval of the validation scenario (total length of the scenario is 20 minutes) is indicated. The grey highlight every minute shows the mode of the workload level ratings for that minute i.e. the workload level that was most frequently rated amongst the 8 ATCOs.

The lower table indicates the output of the workload estimation methodology. The computed perceived complexity is shown in blue bars and horizontal lines are placed in the y-axis to define the correspondence of the perceived complexity to the workload level (Section 8.5). The computed workload level is finally shown in the upper table as a red quadrangle.
Table 9-6 Workload ratings and methodology outputs in validation scenario 1

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
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<td>4</td>
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355
Table 9-7 Workload ratings and methodology outputs in validation scenario 2

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![Graph showing perceived complexity over time](image-url)
Table 9-8 Workload ratings and methodology outputs in validation scenario 3

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![Diagram showing perceived complexity over time](image-url)
Table 9-9 Workload ratings and methodology outputs in validation scenario 4

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Perceived Complexity

Time
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Perceived Complexity

Time

359
Table 9-11 Workload ratings and methodology outputs in validation scenario 6

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It can be observed from Table 9-6 to Table 9-11 that there is a correlation between the ATCOs ratings and the model outputs (correlation between grey cells and red quadrangles), even though this conclusion is weakened by two factors that are quantified later in this section:

- The methodology output follows the ATCOs responses mode trend, although the results do not exactly match the ATCO workload ratings.
- There is a variance in the ATCOs responses that prevents from obtaining a single “actual workload” value.

In order to evaluate the relevance of the first factor (the absolute accuracy of the methodology) accounting for the second factor, an initial analysis is performed consisting in the calculation of the frequency for each scenario when the methodology output matched the ATCOs ratings: the absolute accuracy.

Due to the existence of variability in the ATCOs responses an agreement ratio is defined as percentage of coincident responses amongst the 8 ATCOs above which the workload is considered to have a true value. For instance if the agreement ration is considered to be 50%, it would be sufficient to have 4 ATCOs (50% of 8) rating the workload level to be the same as the actual.

Table 9-12 reflects this analysis for two different agreement ratios 62.5% (5 ATCOs agreement) and 75% (6 ATCOs agreement). The number of times a true workload value was found under the agreement ratio is shown for each scenario and the frequency of matching between the workload true value and the methodology output is calculated as the success ratio.

In addition, Table 9-12 indicates the characteristic workload level during the six validation scenarios to investigate a potential correlation between the number of true workload values and success rate with the average workload. The characteristic workload level is qualitatively defined through the frequency of workload ratings within each workload level.
Table 9-12 Absolute accuracy of workload estimation methodology outputs

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</tr>
<tr>
<td>VL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Workload level</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
<th>Scenario 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium-High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium-Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9-12 shows that for larger agreement ratios the number of true workload measurements found is significantly reduced, even though the success ratio is not necessarily reduced in the proportion. In fact, it can be observed from this table that the number of true workload values increase for the lower workload scenarios and vice-versa.

This finding indicates that ATCOs tend to agree in their ratings during low-workload scenarios whilst it occurs that during high workload scenarios the agreement tends to be weaker.

Finally, Table 9-12 indicates that the success ratio is especially low during scenario 6 (Table 9-11). Session debriefing unstructured discussions revealed that the air traffic scenario was characterised by two arrivals to Brussels airport, which were not accomplished according to nominal procedures due to inability of one aircraft to meet the descent performance clearances. This fact increased significantly the workload and was not captured by the methodology. Ideally, this scenario should have been excluded from the optimal validation scenarios set. However, it was not identified as abnormal during the corresponding validation
Table 9-12 indicates the absolute success ratio of the workload estimation methodology for each defined agreement ratio in order to account for the variability in the ATCOs responses. Besides, as observed from Table 9-6 to Table 9-11 there are clear signs of correlation between the ATCOs ratings and the methodology outputs. This correlation is assessed in Table 9-13.

Table 9-13 ATCOs ratings and methodology Spearman’s rank coefficient

<table>
<thead>
<tr>
<th>Correlation between ATCOs ratings</th>
<th>Correlation of ATCOs ratings - methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BD</td>
</tr>
<tr>
<td>S1 (M/H)</td>
<td>0.29</td>
</tr>
<tr>
<td>S2 (H)</td>
<td>0.73</td>
</tr>
<tr>
<td>S3 (M)</td>
<td>0.37</td>
</tr>
<tr>
<td>S4 (M/L)</td>
<td>0.34</td>
</tr>
<tr>
<td>S5 (M)</td>
<td>0.55</td>
</tr>
<tr>
<td>S6 (H)</td>
<td>0.74</td>
</tr>
<tr>
<td>All Scenarios</td>
<td>0.47</td>
</tr>
</tbody>
</table>

In Table 9-13 the correlation between variables is computed using the Spearman’s rank coefficient for ranked variables (Choi, 1977). In fact, workload ratings are ranked and not continuous data since the difference between workload levels should not be considered linear i.e. the ATCO effort between adjacent workload levels is not always the same amongst the entire workload scale.

The average Spearman’s correlation coefficient for each ATCO and all the scenarios is calculated to assess the correlation of the corresponding workload ratings. Even though some ATCOs tended to consistently rate lower workload levels (Figure 9-6), Table 9-13 shows that the correlation is almost constant across all the ATCOs regardless of their absolute workload.
In the same way, the average Spearman’s correlation coefficient is calculated for each scenario, leading to different levels of correlation that can be attributed to the characteristic workload levels introduced before. In general high workload scenarios have highly correlated ratings whilst medium-low workload level scenarios are less significantly correlated.

Finally, VI in S3 does not vary his rating (is constant) therefore, the correlation coefficient does not exist. This is excluded from further calculations.

The last column in Table 9-13 shows the correlation between the ATCOs responses and the methodology outputs. It can be observed that in the same way as for the correlation between the ATCOs responses, high workload scenarios show strong correlation whilst medium-low workload scenarios show poor correlation levels.

Table 9-14 gathers the findings of the validation analysis.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>High workload</td>
<td>High correlation between ATCOs ratings</td>
</tr>
<tr>
<td></td>
<td>High correlation between methodology outputs – ATCOs ratings</td>
</tr>
<tr>
<td></td>
<td>Low number of true workload values</td>
</tr>
<tr>
<td></td>
<td>Low absolute accuracy methodology outputs – ATCOs ratings</td>
</tr>
<tr>
<td>Medium-Low workload</td>
<td>Low correlation between ATCOs ratings</td>
</tr>
<tr>
<td></td>
<td>Low correlation between methodology outputs – ATCOs ratings</td>
</tr>
<tr>
<td></td>
<td>High number of true workload values</td>
</tr>
<tr>
<td></td>
<td>High absolute accuracy methodology outputs – ATCOs ratings</td>
</tr>
</tbody>
</table>

It can be concluded from Table 9-14 that the methodology accurately estimates the workload trend during high workload scenario measured as the correlation of ATCOs responses to methodology outputs, although no conclusion can be drawn for the absolute workload level estimation due to a lack of agreement between the ATCOs ratings.
On the other hand, during low workload scenarios the methodology is not strongly correlated to the ATCOs ratings, in fact, these are not even strongly correlated between them. In terms of absolute accuracy, during medium low workload scenarios the methodology is accurate (up to 80% success ratio for a 75% agreement ratio) in predicting the workload levels.

9.2.2 Debriefing results

The last part of validation step 5 (workload reconstruction) consists of a session debriefing to identify any potential issues experienced by the ATCOs during the validation task and to assess their satisfaction relative to the validation task (Section 9.1.5.4). The comments and responses to the debriefing questionnaire are shown in Appendix 6. Table 9-15 shows the results of the questionnaire for each of the statements below:

- Statement a: The scenario briefing information is sufficient
- Statement b: The validation scenarios are representative of usual operations
- Statement c: I felt capable of reconstructing the workload
- Statement d: I felt comfortable with the scenarios duration
- Statement e: I consider the workload scale to be appropriate

Table 9-15 Debriefing questionnaire results (1-strongly disagree; 2-disagree; 3-agree; 4-strongly agree)

<table>
<thead>
<tr>
<th>Statement</th>
<th>BD</th>
<th>BQ</th>
<th>BW</th>
<th>CM</th>
<th>KV</th>
<th>RP</th>
<th>VI</th>
<th>XX</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>b</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>c</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>d</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>e</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

In general the ATCOs agreed or strongly agreed with statements $a$ through $d$. In statement $e$, some ATCOs found the workload scale to be inappropriate and used it as a 1-6 numerical scale, ignoring the definition of each level. The implication of this in the validation study is considered to be negligible since what the ATCOs did in these cases was to individually create a workload scale that was found more manageable by them, within the 6-likert type
scale.

During the discussions some ATCOs pointed out that with the replay configuration (radar + voice) it could be possible that the workload ratings did not capture environmental factors such as verbal coordination workload between the EC and the PC or noise, which may add to workload. These types of environmental issues were effectively identified in CHAPTER 8 as a methodology limitation.

Finally, it was recommended to add larger variety of scenarios (however this is constrained by staff availability) and to change the order in which replays are shown in order to assess whether ATCO ratings were dependent on the replays sequence. This is an interesting insight, although it is considered to have a secondary importance and that could not be investigated due to time and staff limitations.

This section has assessed the accuracy the workload estimation methodology for the MUAC DECO sectors group under different conditions and discussed its performance. The next section attempts to achieve the same objective for GUAC.

9.3 GUAC Validation

In order to demonstrate the transferability of the workload estimation methodology developed in CHAPTER 8 this section aims to validate it in another ACC: GUAC. The validation strategy used corresponds to the one used in MUAC in Section 9.1.

Prior to the validation of the methodology in GUAC, a dedicated calibration is required as in the MUAC case. In order to calibrate the methodology, the MUAC methodology parameters configuration is used as a baseline (Section 8.6). The changes in GUAC compared to MUAC should therefore be reflected as changes in these parameters.

Therefore, a direct comparison between MUAC and GUAC is needed in the following areas:

- Data characterisation
- Strategy identification
Skyguide ATC systems are different from those in MUAC, hence the methodology input data (Section 8.2) needs to be thoroughly sourced to ensure consistency in the data sets produced.

Table 9-16 shows the correspondence between the ATCO clearances in MUAC and GUAC. This is of fundamental importance in order to re-write the automatic tool developed to ensure that it is able to analyse GUAC data within their own codes.

### Table 9-16 Correspondence between MUAC and GUAC ATCO clearances

<table>
<thead>
<tr>
<th>Functional Clearance</th>
<th>MUAC code</th>
<th>GUAC code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assume flight</td>
<td>“ASM”</td>
<td>“ENTERING_FLIGHT”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“ENTRY_ACKNOWLEDGMENT”</td>
</tr>
<tr>
<td>Cancel assume flight</td>
<td>“XASM”</td>
<td>“TRANSFER_TO_ADJACENT”</td>
</tr>
<tr>
<td>Cleared Flight Level</td>
<td>“CFL”</td>
<td>“CFL_MESSAGE”</td>
</tr>
<tr>
<td>Direct to point</td>
<td>“D2P”</td>
<td>“CLEARANCE_ROUTE”</td>
</tr>
<tr>
<td>Heading</td>
<td>“HDG”</td>
<td>“HDG_MESSAGE”</td>
</tr>
<tr>
<td>Speed</td>
<td>“SPD”</td>
<td>-</td>
</tr>
<tr>
<td>Entry flight level</td>
<td></td>
<td>“EFL_MANUAL.MODIFICATION”</td>
</tr>
<tr>
<td>coordination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit flight level</td>
<td>“TFL”</td>
<td>“XFL_MANUAL.MODIFICATION”</td>
</tr>
<tr>
<td>coordination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit heading coordination</td>
<td></td>
<td>“COORDINATION_HDG”</td>
</tr>
</tbody>
</table>

In this table it can be observed that most of the functional clearances are generated both in the MUAC and GUAC data set, although the GUAC data set is more complete due to the incorporation of more information regarding to the coordination tasks between adjacent centres and sector. On the other hand, the GUAC does not generate speed clearances data, fundamentally because this type of command is not frequently used in the GUAC.

In order to demonstrate that the methodology is able to accurately estimate workload with the same input data used in the MUAC case, during the GUAC validation the additional information provided by GUAC data set regarding coordination tasks is not incorporated to the workload methodology estimation.
Nevertheless, the incorporation of this data could be translated into an accuracy enhancement of the workload methodology as it directly address the coordination issue identified by MUAC ATCOs during the debriefing sub-step (Section 9.2.2).

After the differences in the two datasets have been captured, the next step aims to ensure that the pre-processing filters applied to MUAC are also applicable to GUAC. In the GUAC case only the inputs duplication filter (Section 8.2.1) needs to be maintained since no training issues or flight delegation issues are identified in GUAC operations.

Finally, it is necessary to verify that the ATC working strategies from MUAC are also valid for GUAC and to identify whether new strategies are used in GUAC. Subsequently, the verification and identification of strategies is translated into modified and new logical rules and their associated complexity vectors (Section 8.4).

In order to conduct this verification the same methodology developed in Section 8.6 is used in the GUAC case:

- Observations and discussions
- Workload reconstruction interviews

A 20-hour observation task is carried out followed by discussions with the ATCOs that were observed in the same manner as explained in Section 8.6.1. During these discussions Table 8-8 was presented directly to the ATCOs in order to identify any potential modification to the MUAC baseline.

Table 9-17 shows the result of the GUAC calibration process after the ATCOs discussions. This table shows that the modifications relative to the MUAC baseline are minimum (highlighted in red). In general these modifications represent larger weight factors in the complexity vectors, which indicate additional complexity when the rules are triggered.

Nevertheless, this similarity between MUAC and GUAC calibration parameters indicate a high transferability of the methodology and its associated baseline parameters.
Table 9-17 GUAC logic rules and complexity vectors calibration

<table>
<thead>
<tr>
<th>Rules</th>
<th>Condition</th>
<th>Weight</th>
<th>Start time</th>
<th>End time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy</td>
<td>-</td>
<td>1</td>
<td>ASM</td>
<td>XASM</td>
</tr>
<tr>
<td>HDG/D2P</td>
<td>Prior to first input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>If D2P</td>
<td>2</td>
<td>ASM</td>
<td>D2P</td>
</tr>
<tr>
<td></td>
<td>If HDG</td>
<td>2</td>
<td></td>
<td>HDG</td>
</tr>
<tr>
<td></td>
<td>Intermediate inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>If D2P</td>
<td>2</td>
<td>D2P</td>
<td>Next D2P or HDG</td>
</tr>
<tr>
<td></td>
<td>If HDG</td>
<td>4</td>
<td>HDG</td>
<td></td>
</tr>
<tr>
<td></td>
<td>After last input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>If D2P</td>
<td>1</td>
<td>D2P</td>
<td>XASM</td>
</tr>
<tr>
<td></td>
<td>If HDG</td>
<td>3</td>
<td>HDG</td>
<td></td>
</tr>
<tr>
<td>SPD</td>
<td>-</td>
<td>4</td>
<td>SPD</td>
<td>Next SPD or XASM</td>
</tr>
<tr>
<td>CFL</td>
<td>Ascent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prior to first CFL</td>
<td>4</td>
<td>ASM</td>
<td>CFL or time level</td>
</tr>
<tr>
<td></td>
<td>Intermediate CFLs</td>
<td>4</td>
<td>CFL</td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>After last CFL</td>
<td>1</td>
<td>CFL</td>
<td>XASM or time level</td>
</tr>
<tr>
<td>CFL</td>
<td>Descent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prior to first CFL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Only 1 CFL</td>
<td>1</td>
<td>ASM</td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>Several CFLs</td>
<td>2</td>
<td></td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>Intermediate CFLs</td>
<td>4</td>
<td>CFL</td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>After last CFL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>With TFL</td>
<td>3</td>
<td>CFL</td>
<td>XASM or time level</td>
</tr>
<tr>
<td></td>
<td>Without TFL</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

369
The final step in the calibration process is the accomplishment of the workload reconstruction interviews through the replay of selected air traffic scenarios (radar + voice) (Section 8.6.2).

Initial discussions held with representatives of GUAC confirmed their capability to conduct these replays, both necessary for the calibration and validation tasks. However, after the start of the research placement in GUAC it was found that the replays could not be conducted due to the following reasons:

- It was not possible to coordinate voice and image (radar) outputs: the replay speed of both outputs is not linear and not correlated.
- It was not possible to conduct the workload reconstruction interviews in low-quality displays (where replay speed is linear) due to the lack of voice replay and low levels of ATCO familiarity with the images shown.

These two reasons prevented the progress of the calibration and validation task in GUAC. Other solutions were investigated to carry out the analysis without the support of the replays:

- Use air traffic simulation scenarios used for training purposes. However, it was found that these scenarios were not realistic and that these simulations would need to be run every time a validation ATCO conducts the workload reconstruction validation step, which would need very intense staff resources.
- Conduct real-traffic validations. However, due to the timing of the research (January-March 2014 – winter season), traffic levels in GUAC were very low and the most likely scenario would have been a very low air traffic scenario. This would have led to very low workload scenarios, which would have not complied with validation requirement 1 (wide workload spectrum).

Therefore, the GUAC validation task was interrupted and not completed due to the technical deficiencies identified above.

9.4 Workload Estimation Methodology Applications

Due to the simplicity and ease of automation of the workload estimation methodology, which is only dependent on input data format for its operation, it can be applied widely and
extensively in order to capture workload trends at high workload levels and absolute accuracy at medium-low workload levels (Tobaruelas et al., 2014b). It can be applied for workload estimation in different environments: from RTS exercises to real-time operations and post-operations.

9.4.1 Real Time Simulation exercises

Traditionally, RTS exercises have been conducted to assess the impact of new operations, technologies and procedures on KPAs such as capacity. In capacity terms, workload has been measured during the RTS to identify its levels in comparison to the baseline scenarios. In Section 4.2.2 the different methods of measuring workload during RTS were discussed. All these methods have in common the problem of interference with the ATCO job, which is overcome with the methodology developed in this thesis.

The workload estimation methodology here developed can be used for workload measurement after calibration in RTS, running in a machine fed by the ATC system completely transparent to the ATCO.

This approach ensures high accuracy levels at medium-low workload scenarios and trend identification in high workload scenarios, along with short preparation and post-processing tasks for workload estimation. The SESAR implementation program through some of the OISs referring to workload reductions shall benefit from this methodology, which would effectively assess whether these reductions would happen with the new implementations. Table 9-18 lists these OISs in the en-route environment.
Table 9-18 – List of SESAR OISs aiming ATCO workload reductions

<table>
<thead>
<tr>
<th>SESAR OI Code</th>
<th>OI step</th>
<th>IOC</th>
<th>FOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUO-0301</td>
<td>Voice Controller-Pilot Communications (En-Route) Complemented by Data Link</td>
<td>31-12-2007</td>
<td>31-12-2016</td>
</tr>
<tr>
<td>AUO-0303-A,B,C</td>
<td>Revision of reference business/mission trajectory (RBT) using datalink</td>
<td>21-12-2021</td>
<td>21-12-2025</td>
</tr>
<tr>
<td>CM-0101</td>
<td>Automated Support for Traffic Load (Density) Management</td>
<td>31-12-2007</td>
<td>31-12-2010</td>
</tr>
<tr>
<td>CM-0102-A,B</td>
<td>Automated Support for Dynamic Sectorisation and Dynamic Constraint Management</td>
<td>31-12-2017</td>
<td>31-12-2022</td>
</tr>
<tr>
<td>CM-0103-A,B</td>
<td>Automated Support for Traffic Complexity Assessment</td>
<td>31-12-2019</td>
<td>31-12-2022</td>
</tr>
<tr>
<td>CM-0104-A,B</td>
<td>Automated Controller Support for Trajectory Management</td>
<td>31-12-2019</td>
<td>31-12-2022</td>
</tr>
<tr>
<td>CM-0201</td>
<td>Automated Assistance to Controller for Seamless Coordination, Transfer and Dialogue</td>
<td>31-12-2008</td>
<td>31-12-2013</td>
</tr>
<tr>
<td>CM-0202</td>
<td>Automated Assistance to ATC Planning for Preventing Conflicts in En-Route Airspace</td>
<td>31-12-2007</td>
<td>31-12-2015</td>
</tr>
<tr>
<td>CM-0203</td>
<td>Automated Flight Conformance Monitoring</td>
<td>31-12-2008</td>
<td>31-12-2016</td>
</tr>
<tr>
<td>CM-0204</td>
<td>Medium Term Conflict Detection with Conflict Resolution Advisories and Conformance Monitoring</td>
<td>31-12-2015</td>
<td>31-12-2018</td>
</tr>
<tr>
<td>CM-0403</td>
<td>Conflict Dilution by Upstream Action on Speed</td>
<td>31-12-2018</td>
<td>31-12-2022</td>
</tr>
<tr>
<td>CM-0404</td>
<td>Enhanced Tactical Conflict Detection/Resolution and Conformance &amp; Intent Monitoring</td>
<td>31-12-2018</td>
<td>31-12-2023</td>
</tr>
</tbody>
</table>

Finally, the methodology can be applied after real-time operations to assess the performance of the ACC operations: sectorisation effectiveness in workload terms, workload safety scenarios or individual ATCO performance. The post-operations application is similar to the RTS exercises use.
9.4.2 Real-Time operations

Since the workload estimation methodology here developed runs in a separate machine to the ATC system and transparent to the ATCO, it can continuously estimate the workload in the different operational sectors of the ACC. This has several applications, with the most important being the real-time workload monitoring.

During ATC operations the EOS make sure that the workload is below thresholds and balanced across the operational sectors. Otherwise, ATFCM and ASM measures are adopted to achieve these two objectives.

Currently workload is evaluated in the different operational sectors by means of direct-questioning of the ATCOs. It is obvious that this can distract the ATCO when the workload is very high. Therefore, the methodology developed introduces a non-intrusive real-time workload estimation method that can be directly presented to the EOS.

Figure 9-7 shows an example of real-time identification of workload imbalances between the DELTA High and DELTA low workload sectors for a given period of time. Given the model performance described in Section 9.1.6, in this example the model cannot conclude if the workload peaks in DELTA High produce an overload (low absolute accuracy in high workload scenarios), but it can be identified when the maximum workload occurs (trend identification capability). In the DELTA Low it can be concluded that workload is consistently very low / low with exception of a 3-minute interval of medium workload (absolute accuracy in medium-low workload scenarios).
9.5 Summary

This chapter has developed a validation strategy to discuss the accuracy of the workload estimation methodology previously developed in CHAPTER 8. The validation strategy consists of a 6-step approach that includes a definition of validation scenarios, identification of the ATCOs for the validation, a workload reconstruction step and a final analysis between the reconstruction outputs and estimated workload.

This validation strategy is applied to two ACCs to demonstrate the transferability of the methodology: MUAC and GUAC.

The validation results in MUAC (Section 9.2.1) show a high correlation of the methodology...
to the ATCOs ratings in high workload scenarios with a lower absolute accuracy due to the inherent variability of ATCOs responses. On the other hand during medium-low workload scenarios, the absolute accuracy of the methodology is very high with a lower correlation to the responses due to the inherent low correlation of the ATCOs ratings during these scenarios.

For the GUAC validation, the MUAC calibration parameters are used as a baseline and their applicability for GUAC is assessed. It is found that the GUAC calibrated methodology is very similar to the MUAC set of parameters, indicating ease of transferability between different ACCs.

Nevertheless, the validation task could not be completed in GUAC due to technical deficiencies at the ACC that prevented developing the workload reconstruction validation step. Therefore, the two-centre calibration was not accomplished and the validity of the methodology relies fundamentally on the MUAC results.

Finally, the applications of the methodology have been discussed for the two main areas of application: RTS exercises and real-time operations. Within the former area, the potential applicability of the methodology to assess the benefit of introducing SESAR OISs is discussed. The application of the methodology to real-time operations is introduced as well.
CHAPTER 10  FRAMEWORK IMPLEMENTATION AND INTERDEPENDENCIES

The framework for the estimation of airspace capacity was proposed in CHAPTER 4 and it was based on a four-step process. Subsequent chapters focused on Step 3 and Step 4 of the framework i.e. application of framework areas and analysis of capacity impact. The cost-efficiency area was discussed in CHAPTER 5, the predictability (ASM/ATFCM) area was discussed in CHAPTER 6 and CHAPTER 7, and the workload area was discussed in CHAPTER 8 and CHAPTER 9.

This chapter focuses on Step 1 and Step 2, resulting in the overall implementation of the airspace capacity estimation framework (Section 10.1). Finally, Section 10.2 discusses the interdependencies between the three framework areas and their impact on the estimated airspace capacity.

10.1  Airspace Capacity Estimation Framework Implementation

The aim of the capacity estimation framework, as stated in CHAPTER 1, is to develop a means to assess the impact of the implementation of modernisation initiatives on en-route airspace capacity.

In order to do this, and based on the identified limitations of existing capacity estimation methodologies (CHAPTER 4), a novel framework formed of four steps is developed (Section 4.5):

1.  Input
2.  Input evaluation
3.  Application of framework areas
4.  Analysis of capacity impact

This framework is depicted in the figure below:
Although from CHAPTER 5 to CHAPTER 9 the three framework areas (ATCO workload, predictability (ASM/ATFCM) and cost-efficiency) have been developed and the analysis of the modernisation initiatives on airspace capacity has been discussed (Step 3 and Step 4), this section discussed the implementation of the overall framework with special focus on Step 2: Input evaluation.

10.1.1 Step 1: Input

Section 4.5.1 describes that the first step in the implementation of the framework consists in a compilation of information on the modernisation initiative or operational improvements as named within the SESAR programme. This information includes:

- Operational and technical specifications of the modernisation initiative;
- Discussions with SMEs; and
- Gathering of historical information from similar modernisation initiatives.

The amount of gathered data depends may suffer great variance depending on the modernisation initiative (e.g. industry owned initiatives may share less technical specifications). In this thesis the modernisation initiatives used have been those reflected in SESAR Master Plan and they are specified in Appendix 2.
10.1.2 Step 2: Input evaluation

The second step of the airspace capacity estimation framework determines which area captures each operational improvement type.

Based on the nature of the operational improvements, each of these can be associated with an area of the capacity estimation framework. For instance, if the impact of a new ATCO automated tool on airspace capacity is being assessed, the workload estimation framework area would reflect the impacts of this operational improvement on the ATM operations and therefore on airspace capacity. Other areas could be secondarily impacted, although their relationships with the operational improvement would be weaker. The existing interdependencies are discussed in Section 10.2.

Therefore, depending on the type of operational improvement being assessed there is a framework area that better captures its effects on airspace capacity. This is depicted in Figure 10-2.

![Figure 10-2 Relationships between operational improvement categories and framework areas](image)

In this figure the operational improvements categories have been divided into the following

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378
six main groups:

- ATC system: includes any modernisation of the ATC system (system used by the ATCOs) that can impact the ATCO job. For instance, this category would include new tools with new predictability capabilities that enlarge the ATCO prediction horizon (e.g. MTCD tool).

- ATCO performance: includes any modernisation initiative that impacts the ATCO performance through different means than the ATC system. New procedures (e.g. airspace design) are embedded in this operational improvement category.

- Situational awareness: includes any modernisation initiative aiming to increase the levels of shared relevant information across the different ATM stakeholders (e.g. SWIM concept).

- Predictability: includes any modernisation initiative that enables increased accuracy of air traffic demand predictions for the development of the ATFCM and ASM functions. The predictability enhancements can occur in one or both of the categories of reduction of the prediction error and extension of the prediction horizons.

- Workforce management: includes any modernisation initiative revising ATCO staff planning processes and contractual agreements and execution of the ASM function.

- Planning buffers: includes any modernization initiative relative to the implementation of the ACC planning process in terms of safety buffers ensuring enough ATCO workforce for the predicted air traffic demand.

Any operational improvement that can be included in one of the categories above can be modelled by the airspace capacity estimation framework through the framework areas shown in Figure 10-2.

This framework is therefore limited to modernisation initiatives that have impact in one at least one of the three capacity factors identified in the framework (cost-efficiency, predictability and workload). Modernisation initiatives that cannot be included in the six-group classification cannot be modelled through the developed framework.
10.1.3 Step 3 and 4: Application of framework areas and analysis of capacity impact

Once a framework area has been selected for analysis, the methodologies developed in this thesis are applied.

- The ACC cost-efficiency framework area (CHAPTER 5) reflects the impacts on airspace capacity caused by changes of the ACC planning process, workforce management procedures and ASM execution performance i.e. the cost-efficiency/capacity trade off.
- The predictability framework area (CHAPTER 6 and CHAPTER 7) enables the quantification predictability buffer due to ASM/ATFCM prediction inaccuracies.
- The ATCO workload framework area (CHAPTER 8 and CHAPTER 9) models the effects of new ATC systems and operational procedures on ATCO workload during RTS, operational trials and real operations.

In summary, the application of the airspace capacity estimation framework requires in first place to gather information relative to the modernisation initiative. Afterwards it requires including the modernization initiative in one of the six modernization categories captured by the framework, which are in turn associated to a framework area. Based on to which category the modernization initiative is associated to, a framework area is be used, which uses the developed methodologies to assess impacts on airspace capacity.

This section has discussed how the framework is implemented. The proposed implementation assumes that a modernisation initiative is uniquely associated to a framework area. However, modernisation initiatives may have secondary impacts on other airspace capacity drivers, and therefore framework areas i.e. there are interdependencies between the framework areas. This issue is addressed in the following section.

10.2 Interdependencies

It has been discussed in the previous section that each modernisation initiative can be classified within an operational improvement category and that each of these categories has
an associated framework area, which captures the effects of the modernisation initiative on airspace capacity.

Nevertheless, it may occur that certain operational improvements have secondary effects on other framework areas due to existence of common drivers in the different framework areas. These interdependencies, which are discussed in this section, are depicted in Figure 10-3.

![Figure 10-3 Interdependencies between framework areas](image)

In this figure the three framework areas are shown in quadrangles. The interdependencies between the framework areas are shown through arrows that indicate the direction (which framework area affects which other framework area) and the means of the interdependence (which is the means that primarily affect a framework area and secondarily another framework area).

The next sub-sections examine the interdependencies between each framework area pair.
10.2.1 Cost-efficiency – Workload

The ACC cost-efficiency, as discussed in CHAPTER 5, is fundamentally driven by the ASM function execution performance and by the accuracy of the planning process that together constitutes the OCE (Section 5.3.3). The OCE can simultaneously impact the ATCO workload through the interdependency of the two framework areas (Figure 10-3).

Large OCE values indicate a high accuracy of the planning process along with an optimized performance of the ASM function. In turn, a good performance of the ASM function indicates amongst others high utilization levels of the airspace sectors (Section 5.2.2). Since air traffic demand is the primary ATCO workload source (Section 3.4), it can be assumed that with larger utilization levels (higher air traffic demand), workload would follow an upward evolution i.e. ACC cost-efficiency and ATCO workload are positively correlated.

This relationship suggests that any operational improvement categorised under the workforce management or planning buffers categories should be analysed in ATCO workload terms after conducting the cost-efficiency assessment, in order to verify that no workload excess occurs.

On the other hand, another interdependency exists between ACC cost-efficiency and ATCO workload. However, in this case, this occurs in the opposite direction i.e. operational improvements primarily affecting ATCO workload can secondarily affect the ACC cost-efficiency.

This effect can typically occur when operational improvements that result in workload changes (ideally reducing the workload) motivate the revision of the sector capacities (ideally increasing these capacities), which can be subsequently translated into further changes of the airspace configuration and of the ASM function performance. It is precisely due to this last factor that the ACC cost-efficiency can be impacted due to changes in the sector capacities or in other words the ATCO workload-limited airspace capacity.

It is not apparent though whether the operational improvement categorised under the ATC system or ATCO performance groups and leading to lower ATCO workload levels would positively or negatively affect ACC cost-efficiency. On one hand the increase of sector
capacities due to lower workload levels would effectively be translated into lower utilization levels for the ACC, given that the airspace demand remains constant. In this case ATCO workload and ACC cost-efficiency would be negatively correlated.

It is noteworthy, however, that provided that the workload decrease leads to a revision of the existing airspace configuration, which would ideally be translated into fewer operational sectors, the planning process accuracy would be positively impacted. In fact, with the presence of fewer operational sectors the planning process should be more accurate. Since the number of airspace configuration options are being reduced and so does the uncertainty of the airspace configuration prediction. In this case ATCO workload and ACC cost-efficiency would be positively correlated.

Therefore, it is reasonable to assume the existence of an ATCO workload – ACC cost-efficiency relationship through the revision of sector capacities and airspace configuration, although the individual features of each operational improvement would dictate the specific nature of this relationship.

10.2.2 Workload – Predictability (ASM/ATFCM)

A two-fold relationship exists between the ATCO workload and the ASM/ATFCM predictability framework areas. The first interdependency is associated with the effects of operational improvements affecting the ASM/ATFCM predictability that can secondarily affect the ATCO workload; the second interdependency in contrast involves operational improvements that affect the ATCO workload area that can secondarily affect the ASM/ATFCM predictability.

Regarding the first relationship, increased levels of predictability lead to an enhanced performance of the ASM/ATFCM functions, through the implementation of new procedures such as pre-tactical de-confliction (CHAPTER 7). As discussed throughout this thesis the aim of the ATFCM and ASM functions is to support the development of the ATC function, in order to ensure that air traffic demand does not exceeds the ATC function capacity, which is primarily measured by the ATCO workload.

Increased performance of the ATFCM/ASM functions, can therefore lead to reduced ATCO workload.
workload levels. In this way, ASM/ATFCM predictability and ATCO workload are negatively correlated, with larger values of the former leading to lower values of the latter.

The second ASM/ATFCM predictability – ATCO workload relationship is associated with the effect that ATCO workload reduction measures can have on the predictability levels. As introduced in Section 10.1 the operational improvements associated with ATCO workload can be grouped under the ATC system and ATCO performance categories. This last group embeds amongst others new procedures and operations that aim to reduce ATCO workload.

The introduction of new procedures (e.g. direct routeing) and operations (e.g. free-route environment) can in contrast, have a negative effect on the ASM/ATFCM predictability due to the execution of non-nominal operations. As discussed in CHAPTER 6 the ASM/ATFCM predictability levels rely on the trajectory algorithms carried out by the prediction system (e.g. ETFMS in Europe). If the operations differ significantly from those stated in the flight plans or from those communicated to the stakeholders, the predictability levels will suffer inevitably decreases.

Therefore, it needs to be assessed whether the implementation of operational improvements contributing towards decreased workload levels have a negative effect on the ASM/ATFCM predictability area.

10.2.3 Predictability (ASM/ATFCM) – Cost-efficiency

Larger prediction horizons can positively affect the ACC cost-efficiency through decreased uncertainty and larger accuracy. However, the ASM/ATFCM predictability developed in CHAPTER 6 deals with different time-horizons compared to those present during the planning process (Figure 2-8). Therefore the relationship between the ASM/ATFCM predictability and the ACC cost-efficiency is not due to a better predictability of the planning function. In fact, this relationship is similar to the one occurring between the ATCO workload and ACC cost-efficiency due to the revision of the sector capacities and airspace configuration (Section 10.2.1).

Larger sector capacities due to better predictability levels created by increased ATFCM performance (Section 7.2.2) can be translated into lower cost-efficiency levels due to reduced

384
utilisation figures given that the air traffic demand stays constant. In this case the ATFCM predictability and ACC cost-efficiency would be negatively correlated.

Provided that the increases in ASM/ATFCM capacity due to enhanced predictability levels lead to a revision of the airspace configuration, ideally reducing the amount of existing operational sectors, the ACC cost-efficiency would be positively impacted due to a reduction of the uncertainty associated with the prediction of the required number of operational sectors during the development of the planning process. In this case the ATFCM predictability and ACC cost-efficiency would be positively correlated.

In addition, an increase of the ASM predictability would theoretically lead to an optimised ASM performance. This performance increase would be reflected in an enhancement of the AEP (Section 5.3.2), finally leading to increases of the ACC cost-efficiency given invariable planning process accuracy. This indicates a positive relationship between ASM predictability and ACC cost-efficiency.

The interdependency between the ASM/ATFCM predictability and ACC cost-efficiency framework areas are demonstrated through the three means introduced above, even though the positive or negative nature of the interdependency will depend on the specific nature of each operational improvement.

10.3 Summary

This chapter has described the implementation of the capacity estimation framework in its four steps:

- Step 1 involves gathering relevant information associated to the modernisation initiative to support Step 2.
- A six-group taxonomy is used to classify the modernisation initiatives in Step 2. Each of the groups in the taxonomy is in turn associated to a framework area.
- In Step 3 and Step 4 the methodologies developed from CHAPTER 5 to CHAPTER 9 are used and the impact on airspace capacity is discussed

In addition, this chapter has discussed the potential interdependencies between the airspace
capacity estimation framework areas.

This chapter concludes the development of the airspace capacity estimation framework developed throughout the thesis.
CHAPTER 11  CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This chapter concludes the thesis with the review of the initial research objectives (Section 11.1) and the identification of the main achievements and impacts of the research (Section 11.2). In addition, it discusses the direction that future research should take (Section 11.3). Finally, it lists the publications (Section 11.4), awards (Section 11.5) and patent applications (Section 11.6) resulting from this work.

11.1 Revisiting Research Objectives

This section assesses the completion of the research objectives defined in Section 1.2 prior to the execution of the research.

The research aim is “to develop a framework that assesses the impact of ATM modernisation initiatives on airspace capacity”. This aim has been accomplished through the development of a four-step framework:

Figure 11-1 Airspace capacity estimation framework
Other three research objectives were formulated at the beginning of the thesis. The first one is “the identification of airspace capacity factors based on critical literature review and discussions with Subject Matter Experts (SMEs).” This objective was accomplished in CHAPTER 3 and formed the foundation of the airspace capacity estimation framework. In fact, the resulting airspace capacity drivers from this analysis corresponded to each of the three framework areas.

The second objective aimed “the modelling of these factors”. This objective has been accomplished in three different parts in relation to the three framework areas. Each framework area has discussed the accuracy of the developed models through qualitative discussion (CHAPTER 5), quantifiable performance evaluation (CHAPTER 7) or validation techniques (CHAPTER 9).

The last objective is the “implementation of the framework modelling methodologies in representative Air Traffic Control (ATC) centres in Europe, contributing towards optimising current performance and assessing the adequacy of future deployment plans.” This last objective has been accomplished throughout the thesis with the implementation and assessment performance of the framework areas to two ACCs: MUAC and GUAC. In addition real data from these ACCs has been used to develop and implement the different theories and models as indicated in Table 11-1.

Table 11-1 Data usage type for the different ACCs and chapters

<table>
<thead>
<tr>
<th>MUAC</th>
<th>GUAC</th>
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<td>CHAPTER 5</td>
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<td>CHAPTER 8</td>
<td>Development</td>
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<tr>
<td>CHAPTER 9</td>
<td>Implementation</td>
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</table>

11.2 Main achievements

The table below summarises the main achievements accomplished in each of the chapters.
In addition, based on the results obtained during the development and application of the framework areas the thesis has qualitatively discussed the impacts of SESAR modernisation initiatives in airspace capacity. A total of 53 OISs (16% of the SESAR program) have been included in this discussion.

### 11.3 Future work

Throughout the thesis, the framework limitations and potential enhancements have been identified. This section summarises them and proposes guidelines for future work.
11.3.1 Enhancement of workload estimation methodology

The workload estimation methodology shows significant accuracy (up to 80% of actual workload) during medium-low workload scenarios. However, during high workload scenarios it only demonstrates ability to follow the workload trend but not to estimate the actual workload. Further investigation of this issue would enable more accurate results of the framework.

There are three factors that could potentially drive the low accuracy results and that should be investigated for achieving enhanced methodology results:

- Enhanced workload scale

Some ATCOs indicated during the debriefing session that the workload scale was not suitable for the study (Section 9.2.2). This could have led to erroneous actual values that subsequently turned into low accuracy results. An investigation of other workload scales can therefore result into a methodology improvement.

- Inability to capture non-linear effects during high workload scenarios

The methodology assigns different perceived complexity vector weights to the different ATCO inputs depending on the sequence of clearances and the relative time. However, during high workload scenarios validation results are not sufficiently accurate (Section 9.2.1) suggesting that a different set of weights could be used in these conditions.

The investigation of dynamic weights, which are a function of the estimated workload in previous instants, is considered as a potential field for methodology enhancement.

- Inability to capture other workload drivers

During the debriefing session ATCOs indicated the existence of other workload drivers that were not captured through the methodology. These factors can be environmental factors (e.g. operations room noise) or complexity factors (e.g. bad weather).

A quantification of the estimated workload variance due to the presence of other factors
would indicate the ability of the methodology to be used when these other factors are present, hence increasing confidence in its results.

Finally, the ability of the workload estimation methodology to capture ATCO workload in long-term automation scenarios, especially with the introduction of new roles (e.g. Multi Sector Planner), should be assessed.

The introduction of new roles is expected to result into the creation of new tasks and workload drivers, due to the existence of significant differences in the ATCO work. Even though, in previous chapters it has been shown the potential of the methodology to capture different working scenarios with the calibration of the complexity vector, the introduction of new tasks and objectives, and their implication on workload terms should be thoroughly discussed.

11.3.2 Modelling of framework areas interdependencies

As discussed in Section 10.2 some modernisation initiatives that are modelled through a framework area and are modelled as having an impact on one specific capacity buffer (workload, predictability or cost-efficiency), could as well have a secondary impact on another capacity buffer, this reflecting the interdependencies of the framework areas.

Section 10.2 achieved a qualitative discussion of the framework areas. A quantification of these interdependencies identified should be a future area of work for improving the overall framework and refining the capacity results.

For this quantification the following process is suggested:

1. Identify a modernisation initiative that can potentially impact different framework areas;
2. Obtain a data set for each of the three framework areas during the same period so that the impact of a modernisation initiative can be quantified through the three framework areas; and
3. Perform a pre / post analysis (Section 5.3) to measure the effect of the modernisation initiative in each of the framework areas and their potential correlations.

11.3.3 Quantification of the cost-efficiency buffer

The cost-efficiency buffer, measured as an occupancy value, could not be quantified due to data unavailability. However a methodology was proposed in Section 5.4.3 for its quantification. In order to evaluate the validity of these results it is necessary to obtain the data set identified and apply it to the proposed methodology (Section 5.4.3).

Furthermore, given the current economic situation in Europe, it would be useful to obtain a monetary value for the capacity / cost-efficiency buffer. This would enable ACCs across Europe to quantify the cost of an inaccurate planning process or ASM function performance.
## 11.4 Publications

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11.5 Awards

The following awards were obtained during the development of the thesis:

- SESAR Young Scientist Award, SESAR Scientific Committee, 2014 Madrid
- SESAR award for scientific excellence, SESAR Scientific Committee, 2012 Braunschweig.
- Best PhD paper award, The Boeing Company, ATACCs, 2012 London.

11.6 Patent applications

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## APPENDIX 1

### 2 DECO SECTOR CONFIGURATIONS

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Operational Improvement Steps

An Operational Improvement is any operational measure or action taken through time in order to improve the current provision of ATM operations. Operational improvements are not necessarily isolated exclusively to the effect of a change in technology; they can relate to procedures, working methods or routines and human factor aspects.

Operating Environments:
- Airport
  - Airport Very High Capacity Needs
  - Airport High Capacity Needs
  - Airport Medium Capacity Needs
  - Airport Low Capacity Needs
- TMA
  - TMA Very High Capacity Needs
  - TMA High Capacity Needs
  - TMA Medium Capacity Needs
  - TMA Low Capacity Needs
- En Route
  - En Route Very High Capacity Needs
  - En Route High Capacity Needs
  - En Route Medium Capacity Needs
  - En Route Low Capacity Needs
- Network
  - Network
  - Unassigned

Key:
- Display Baseline
- Research & Development

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431
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Source: European ATM Master Plan Portal
Page 5 of 5
13 April 2014 Data version v003.00 Dataset 3

432
APPENDIX 3

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**Event(s)**

ATC Incident - LATCC - Clacton Sector - Alleged overload between 1605-1700hrs.

CAA Closure: Investigations indicate that due to sickness the Traffic Manager was absent and an ATSA Traffic Co-ordinator was redeployed to Flow Management Planning. There was also a shortage of CSCs and the Watch Supervisor was released to act as a CSC. The initial problem faced by the CSC was with a military a/c that needed a UHF frequency as his VHF was u/s, this taking an excessive amount of effort between 1606-1614. At 1614 he was advised by TC to slow EGLL inbounds as a change to 27L would occur at 1630. Delays started to build due to a number of go-arounds and the expectation of opening R/W 23 at EGLL. The landing rate was only reduced from 36/60 to 32/60 even though the R/W23 landing rate is 15-20/60. At 1622 EGLL stopped landing traffic approaching R/W09L due weather and EGLL Tower advised TC that R/W23 would be in use from 1630 (but it did not become available until 1639). At 1630 TC advised the CLN CSC that they could take 2 more a/c then no more. The landing rate was adjusted to 14/60 and delays increased to 90 minutes. At 1637 the CLN CSC was advised that nothing was landing at Heathrow and R/W23 would be used from 1639. The delay of 14 minutes meant that the CSC had to devise his own tactics to protect the sector and this led to a very high workload in coordination messages. Appropriate local ATC action has been taken to review the process of information exchange between TC and AC in respect of ATM flow issues.
APPENDIX 4

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APPENDIX 5

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-EOBT 2340
-AOBD 130217
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-ADA 130218
-ATA 0445
-ADEP GCLP
-ADES ESMS
-MODELTYP ACT
-ARCTYP B738
-IRULES IFR GAT IFPSTART
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-VEC RELDIST 13 -FL F360 -ETO 130218003800
-PT PTID BENTU -FL F360 -ETO 130218005038
-PT PTID BAROK -FL F360 -ETO 130218010233 -PTRTE DCT
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440
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-ASP -AIRSPDES ESMMTOT -ETI 130218043442 -XTI 130218044555
-END ASPLIST
-RDYSTATE IN
-TAXITIME 0010
-AOARCID NAX
-FLTYP S
-REG LNDYG
APPENDIX 6
evel at each tablet query (every minute)
Workload Reconstruction

Scenario 1
- 18/10/2013 – Friday
- 11:40-12:00 UTC
- Operational sector: DIL
- Airspace configuration: 3.1 (last 3 minutes Holstein is open)

Scenario 2
- 21/10/2013 – Monday
- 08:45-09:05 UTC
- Operational sector: DIL
- Airspace configuration: 3.2 and 4.1 (last 5 minutes)

Scenario 3
- 18/10/2013 – Friday
- 08:50-09:10 UTC
- Operational sector: DBH
- Airspace configuration: 4.1
Scenario 4'
- 24/10/13 - Thursday!
- 10:00M 0:200UTC!
- Operational!Sector: DDH!
- Airspace: configuration: 3.1!


Scenario 5'
- 31/10/13 - Thursday!
- 20:40M 1:000UTC!
- Operational!Sector: DDH!
- Airspace: configuration: 52!


Scenario 6'
- 07/11/13 - Thursday!
- 07:40M 8:00!
- Operational!Sector: DDH!
- Airspace: configuration: 3.2!
Session 'Debriefing'

Indicate your position in respect to the following statements being:

1: Strongly disagree!
2: Disagree!
3: Agree!
4: Strongly Agree!

- The scenario/briefing information is sufficient!

  1  2  3  4

- The validation scenarios are representative of usual operations!

  1  2  3  4

- I felt capable of reconstructing the workload!

  1  2  3  4

4
• I felt comfortable with the scenarios’ duration!

1! 2! 3! 4!

• I consider the workload scale appropriate!

1! 2! 3! 4!

• Other comments!

5
Validation Booklet

Mrs. Catherine Moesen
03/12/2013
Session Debriefing
Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient
  ![Image of 1 2 3 4 choice]

- The validation scenarios are representative of usual operations
  ![Image of 1 2 3 4 choice]

- I felt capable of reconstructing the workload
  ![Image of 1 2 3 4 choice]
- I felt comfortable with the scenarios duration
  1 2 3 4

- I consider appropriate the workload scale
  1 2 3 4

- Other comments

  include external stimuli into the rating system
  => here we only see the "new" EC work, other
  we do not know what is going on around
  him, which is also increasing his workload
  ex: opening / closing sectors
  hand over
  training on EC position
  noise on other sectors.
Session Debriefing

Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient
  
  1 2 3 4

- The validation scenarios are representative of usual operations
  
  1 2 3 4

- I felt capable of reconstructing the workload
  
  1 2 3 4
- I felt comfortable with the scenarios duration
  
  ![Rating Scale] 1 2 3 4

- I consider appropriate the workload scale
  
  ![Rating Scale] 1 2 3 4

  "Difficult to judge whether or not actions are made strategically, tactically or as a reaction."

- Other comments
Session Debriefing
Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient
  

- The validation scenarios are representative of usual operations
  

- I felt capable of reconstructing the workload
  

460
- I felt comfortable with the scenarios duration

- I consider appropriate the workload scale

- Other comments

  sometimes hard to make a picture of the coordination possibly adding to the workload.
Session Debriefing
Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient

  1 2 3 4

  X

- The validation scenarios are representative of usual operations

  1 2 3 4

  X

- I felt capable of reconstructing the workload

  1 2 3 4

  X
- I felt comfortable with the scenarios duration
  
  1 2 3 4

- I consider appropriate the workload scale
  
  1 2 3 4

  too small

  MEDIUM button

  6 different scale on tablet than
  on paper = confusing.

- Other comments

  Good luck!
Validation Booklet

Mr. Bilal Osmon
05/12/2013
Session Debriefing
Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient

- The validation scenarios are representative of usual operations

- I felt capable of reconstructing the workload
• I felt comfortable with the scenarios duration

1 2 3 4

x

• I consider appropriate the workload scale

1 2 3 4

x

• Other comments
Validation Booklet

Mr. Kristlaan Van de Velde
05/12/2013
Session Debriefing
Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient

- The validation scenarios are representative of usual operations

- I felt capable of reconstructing the workload

Some more variety? (most exercises are Delta Sector)
- I felt comfortable with the scenarios duration

1 2 3 4

- I consider appropriate the workload scale

1 2 3 4

- Other comments

Changing the order of the samples might deliver different results.
Validation Booklet

09/12/2013
Session Debriefing

Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient
  \[1\ 2\ 3\ 3\]

- The validation scenarios are representative of usual operations
  \[1\ 2\ 3\ 4\]

- I felt capable of reconstructing the workload
  \[1\ 2\ 3\ 4\]
• I felt comfortable with the scenarios duration

1 2 3 4

• I consider appropriate the workload scale

1 2 3 4

• Other comments
Session Debriefing
Indicate your position in respect to the 5 following statements being:

1: Strongly disagree
2: Disagree
3: Agree
4: Strongly Agree

- The scenario briefing information is sufficient
  1 2 3 ✗

- The validation scenarios are representative of usual operations
  1 2 3 ✗

- I felt capable of reconstructing the workload
  1 2 3 ✗
• I felt comfortable with the scenarios duration

1 2 3 x

• I consider appropriate the workload scale

1 2 3 x

• Other comments