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Life Cycle Assessment in Engineering Design

by

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The necessity to decide is always larger than the amount of our knowledge. *Immanuel Kant*
The danger is that our power to damage or destroy the environment or one another is increasing much more rapidly than our wisdom in using this power. *Stephen Hawking*

Abstract

Making correct design decisions during the early stages of the engineering design process is increasingly seen to be important, as changes during the later stage can be costly. Life Cycle Assessment (LCA) is used as a method to evaluate the design from 'cradle to grave'. In concept design, decisions are made that have a most significant influence on the life cycle, but at this stage the lack of detail makes LCA very difficult if not impossible.

This thesis introduces a method that enables an 'order-of-magnitude' life cycle assessment during the concept stage of the design process. This is achieved by modelling the life cycle inventory as a function of design parameters for complete product families used in engineering design. The hypothesis is that relatively few so-called life cycle parameters determine the largest part of the life cycle inventory. Furthermore, design parameters are related to life cycle parameters, which are mathematically modelled. Design parameters are chosen so that they can be estimated early during the design process. The models of the life cycle parameters are expressed in terms of upper and lower limits, summarising data from many product families. More detailed models describe the relationships of single product families. The method is suitable for software implementation, which will especially aid the handling of sensitivity analysis.

Two case studies (sealed lead acid batteries, three-phase asynchronous motors) are used to illustrate how the life cycle parameters are related to the design parameters. An overall outline of how the method is implemented into the overall design process completes the thesis (evaluation of parallel and series configuration hybrid electric vehicle).

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1 Introduction

1.1 Thesis Overview

Life Cycle Assessment in Engineering Design addresses the problem of performing an estimative, quantitative assessment of an engineering design in the early phases of the design process, taking into account all the phases of the life cycle. The final aim of carrying out such an assessment is to make valid decision with respect to the whole life of the product, from the time the material is extracted from the earth to the time the product's materials enter the earth again at the end of the product's life. This 'cradle to grave' assessment involves the determination of an inventory that includes untreated waste streams to the air, water and earth at intermittent life cycle stages. The amount of data associated with such inventories is immense and difficult to come by, consequentially making life cycle assessment expensive.

Making valid design decisions with respect to the whole life cycle. What does this mean? In short, to select *a* best way of fulfilling a set of requirements with the options available, to find an optimum. Here 'a best way', as opposed the 'the best way' is chosen, since there mostly is no single best way to the problems associated with the life cycle of engineering products. An optimum, in terms of life cycle assessment, is to minimise the harm associated with the untreated waste streams linked to the product directly or indirectly, over the whole life cycle. Harm in this context is effect on the biosphere[1], that has a regional or global, a short term or long term, a direct or indirect negative impact on the ability for *humans* to live. Consequentially, the aim is to keep the earth inhabitable for humans for the future. But, why should individual companies and their individual designers and engineers be interested in such an exceptionally large aim, that it is impossible for the individual to have any significant influence? Life cycle assessment of a product aims to minimises harm on a small scale, and on the other hand, highlights inefficiencies in engineering terms. Thus a life cycle optimised product, is a more competitive product over the whole life cycle than a non-optimised

[1]The regions of the earth's crust and atmosphere occupied by living organisms.

product, especially in a business environment, where there is a significant price on the generation of untreated waste streams and their associated impact.

As with all decision problems, the decisions are based on various assessment criteria which are used to measure the suitability of an option. The assessment criteria (from environmental impact assessment) in life cycle assessment are themselves based on some subjectivity, which is a problem in itself. The assessment criteria themselves are *not* part of this thesis, but some are discussed , as it is part of a complete life cycle assessment and differentiates most life cycle assessment approaches.

The major problems associated with the application of life cycle assessment in a real design environment, is the large cost of gathering the data required to build up a life cycle inventory. The focus of this thesis is to introduce a method aimed at concept evaluation, that minimises the amount of data the analyst has to gather. It involves a substantial amount of work beforehand, but over the 'whole life cycle' of a multitude of life cycle assessments, the effort and time associated with carrying out a life cycle assessment will be less.

Chapter 2 introduces issues of life cycle assessment and engineering design, to set the background of this thesis and to put this work in context. In Chapter 3 a new methodology is developed for assessing the life cycle of a design in the early stages of the design process. It is based on modelling the inventory of standard products used in engineering design. The aim is to obtain an estimative life cycle inventory, which can be used in a life cycle assessment procedure. Chapter 4 contains case studies where the life cycle inventory is modelling. They highlight the procedures required and demonstrate how the life cycle inventory information is condensed. The use of the life cycle inventory models in a life cycle concept assessment situation is demonstrated in Chapter 5, where the models of the previous chapter are used to evaluate two design concepts, able to fulfil the same task.

1.2 Background Information and Requirements

In recent years many methods and tools have been developed to aid the integration of environmental considerations into the design process (e.g. [Müller & Oestermann 1997*a*, Schott, Grüner, Büttner, Dannheim & Birkhofer 1997]). These are aimed at allowing the designer to make informed decisions on the life cycle performance in environmental and monetary terms. However the designer and/or the design team have to consider among others the fulfilment of the functional requirements, manufacturability, cost requirements, maintainability, aesthetics, safety and also environmental and sustainability considerations. With respect to cost more than 70% of the life cycle cost are committed to the product during the early stages of the design

process [Ullman 1997]. The question why it should be any different with 'committing' untreated waste streams and associated environmental impacts in this initial stage of design has yet to be answered. Bhamra, McAloone & Evans [1997] have shown that decisions concerning the life cycle have to be taken as early as possible. This phase was called the critical phases of design and included the specification and the concept design. It was furthermore concluded that

> "pollution is most effectively prevented in the earliest stages of design" [Keoleian & Menerey 1993].

Considering this it can be hypothesised that a substantial part of the total environmental impact of a product is committed in the early stages of design. The hypothesised function of the committed and actual environmental impacts against the life cycle stages is shown in **Fig. 1.1**.

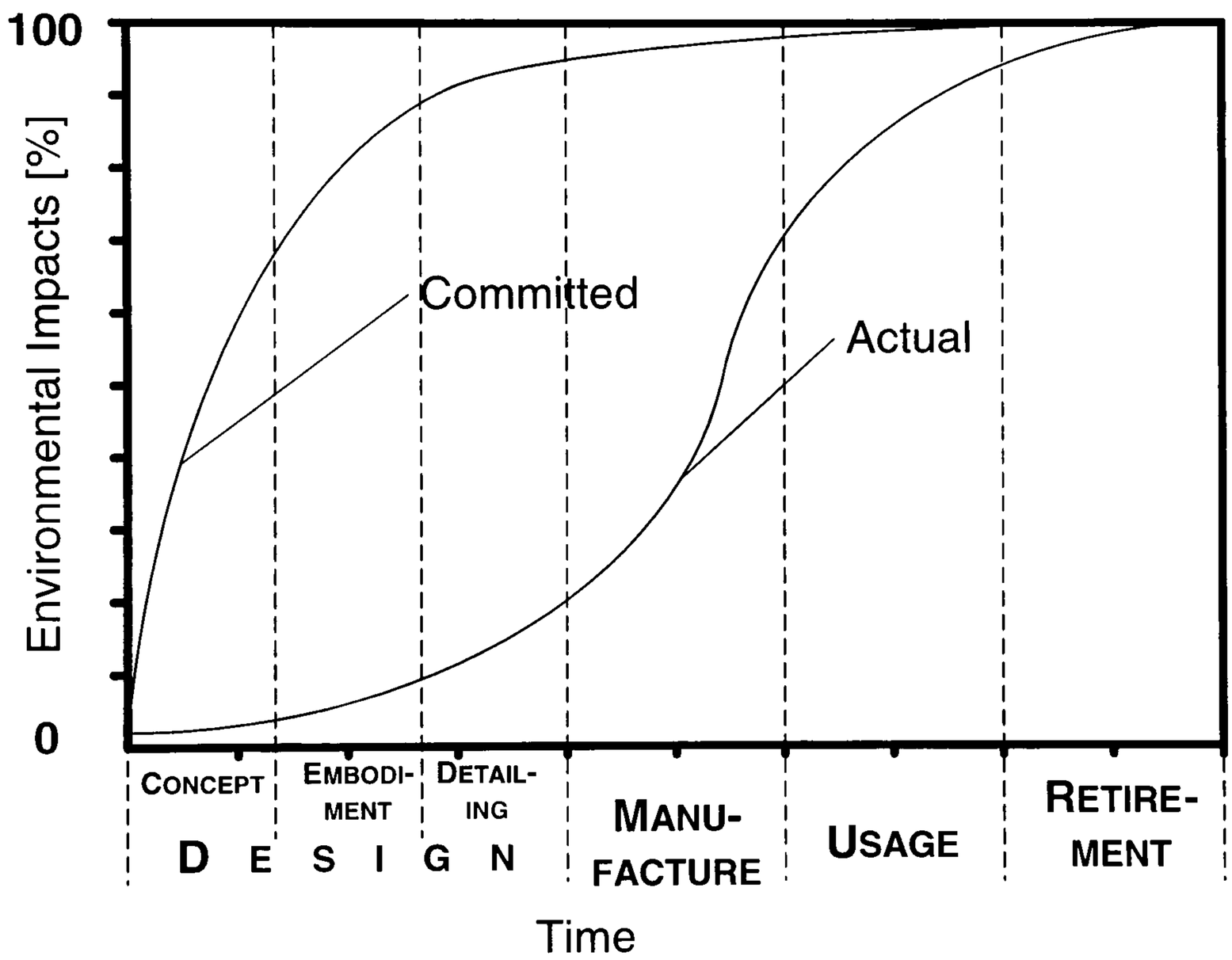


Figure 1.1: Hypothesised relationship between committed and actual environmental impacts against life cycle stages

The innate characteristics of the design process make changes during the early stage of design less costly than at later stages during the design and manufacturing process. The cost associated with changes to the design increases by a factor of 10 for each design stage and changes in the manufacturing stage can cost more than 1,000 times the amount that would have been required if the decision would have been reached during the concept stage [VDI-Richtlinie 2210 1975]. This is illustrated in **Fig. 1.2**.

Therefore, it is important to realise that advantages of methodological approaches compared to intuitive approaches are utilised from as early as possible during the actual

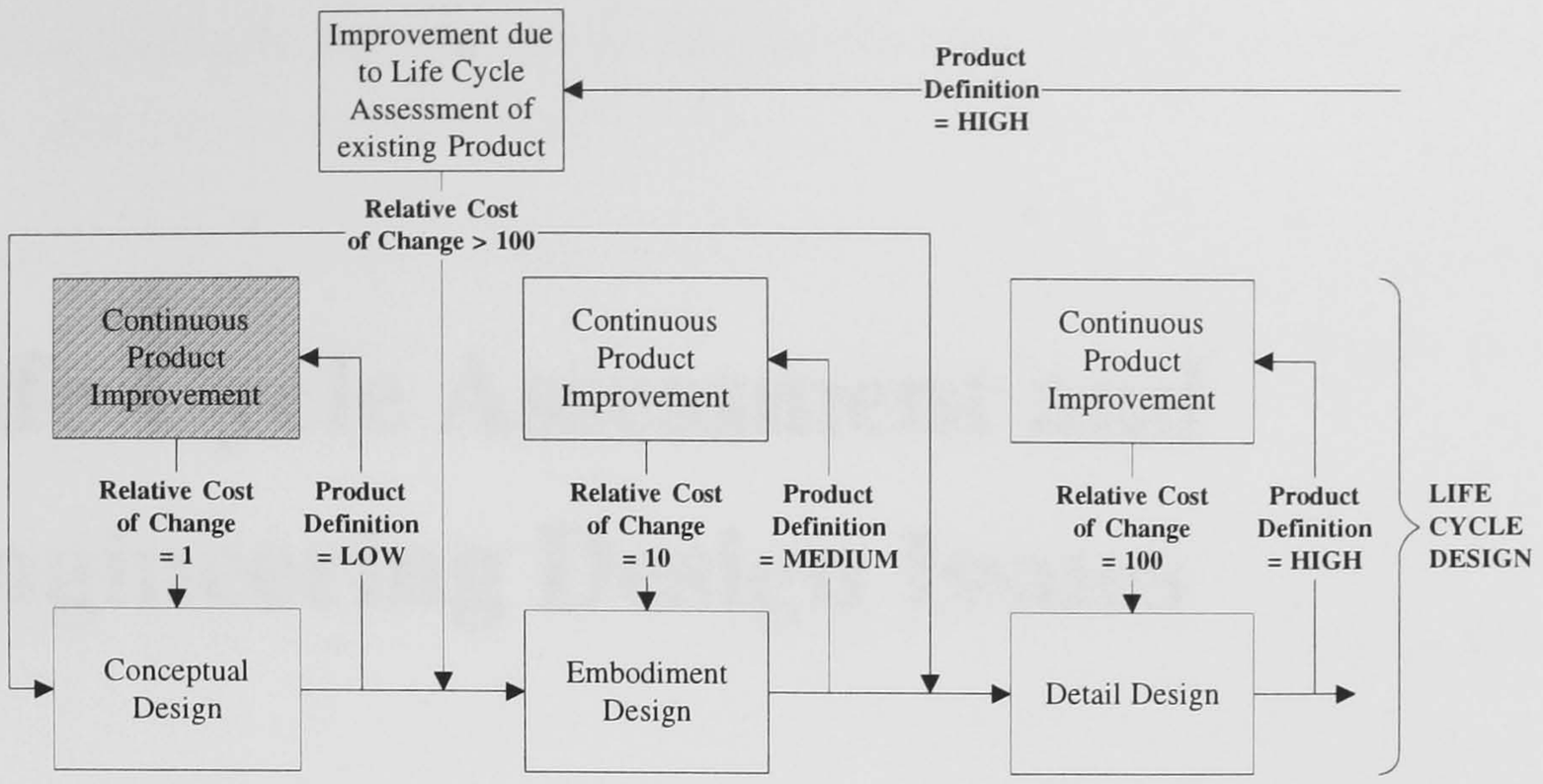


Figure 1.2: The relative cost of change and the product definition conflict

design process, as this allows products and services to be more efficiently designed [Müller & Oestermann 1997*a*]. This is achieved by means of an early recognition and avoidance of mistakes and the associated reduction in the required number of iterations during the design process.

The above also illustrates that a company will be reluctant to allow changes to the design if the changes are introduced at a later stage and the overall life cycle cost reduction cannot justify the incurred cost. This is a scenario that can be easily imagined when one tries to reduce the life cycle environmental impact for no additional cost or even for an overall reduction in life cycle cost. Therefore, it is of importance to make valid Life Cycle Design (LCD) decisions from as early in the design process as possible. It can be seen that as the definition of the product is very low during the conceptual design stage, this lack of information about the product has to be compensated by some other means, so that the product improvement can begin during the conceptual stage where the cost of changing the design is lowest.

This short introduction has illustrate that there is a need for methods that allow the designer to carry out a rough life cycle analysis of the design. The method for life cycle analysis must fulfil the following criteria for its usefulness to a designer:

1. It must be easy to use and require a minimum amount of additional effort related to gathering the data that is required for carrying out the LCA.
2. It must allow for variable levels of definition of the design at the various design stages.

Incorporating a LCA method with the above criteria into the design process allows the designer to test the design from the early stages of the design process and as the design becomes more detailed the designer can make new assessments with reduced uncertainty.

2 Life Cycle Assessment and Engineering Design Issues

2.1 Overview

In this chapter previous work is being reviewed that is important to life cycle assessment and to design in general. The topics covered are

DESIGN PROCESS Section 2.2: In this section the engineering design process is discussed, highlighting the problems due to the lack of detail at the early stages of the design process and the iterative nature of design, into which life cycle assessment should be included as one tool among others to assess a design (the main topic of this thesis).

DESIGN OBJECTIVES Section 2.3: Design objectives are consequences from the need of satisfying requirements in the different life cycle stages. Here the different Design for X's, the life cycle design concept and process planning are shortly discussed.

LIFE CYCLE ASSESSMENT Section 2.4: The procedures of life cycle assessment are discussed, including inventory analysis and environmental impact analysis. The complexity and problems associated due to gathering and evaluating the large amount of data are highlighted.

GROSS ENERGY REQUIREMENT Section 2.5: The determination of gross energy requirement has been established long before life cycle assessment was conceived. The two methods share many aspects; in fact life cycle assessment incorporates gross energy requirement as one measure among others and this section includes aspects relevant to life cycle assessment.

COST MODELS Section 2.6: The inclusion of costing in this context is based on the fact, that costing has been a primary focus in the design process for many decades and the research in this area is considerable. It is anticipated that ideas

form costing procedures can be utilised in enabling the assessment of the product life cycle in concept design.

LIFE CYCLE ASSESSMENT IN ENGINEERING DESIGN Section 2.7: Previous methods for the inclusion of life cycle assessment into the design process are summarised.

FURTHER CONSIDERATIONS Section 2.8: Representing variability with fuzzy numbers and a method to represent data confidentiality, which may be used to rule out data or use data in an assessment tool is shortly introduced.

SUMMARY Section 2.9: A summary of the maim topics of this chapter is given at the end.

2.2 Design Process

All products that are manufactured will have been designed at some stage prior to the manufacturing. Pahl & Beitz [1996] wrote what is widely considered a key work on engineering design, their design methodology is widely taught today. They identify three types of design:

ORIGINAL DESIGN: the principal functional solution for an existing, modified or new requirement is original

ADAPTIVE DESIGN: the design of a known system (functional solution remains) is adapted (form, material) to perform new requirements, often extending capability which may require original design of subassemblies and parts.

VARIANT DESIGN: varying size and/or position within the predefined limits of of the system. Form, function and functional solution remain largely unchanged.

In practice the majority of design tasks are of an adaptive type, often starting at a high level of detail. A typical scenario is the design of a new product generation, where the previous product model's design information forms the basis of the adapted design.

The design process was classified into three levels of increasing detail [Pahl & Beitz 1996]:

CONCEPT PHASE A set of original product requirements are transferred into workable concepts, but at a low level of detail.

In the early phases of the designing process about 70% of the total life cycle cost is actually determined although the whole design process accounts for only 5% of the products cost [Boothroyd 1988, Oakley 1993, Ullman 1997]. Also

the cost associated with 'experimenting' with different design concepts is lowest but on the other hand these 'mental' experiments suffer from the lack of detail that is available at later stages in the design process. It is therefore important to incorporate into any design method aimed at the concept stage these elements of low level of detail and uncertainty.

EMBODIMENT PHASE The embodiment phase follows the concept phase and entails a much larger amount of detailed information. In embodiment design the sketchy details from the concept are taken to a level at which the design can be implemented. This increased detail of information is ideal for carrying out LCA's with sufficient detail to check the validity of the assumptions and calculations made in the concept phase.

DETAILING PHASE In the detailing phase the embodiment design is finalised to a level of detail sufficient for production.

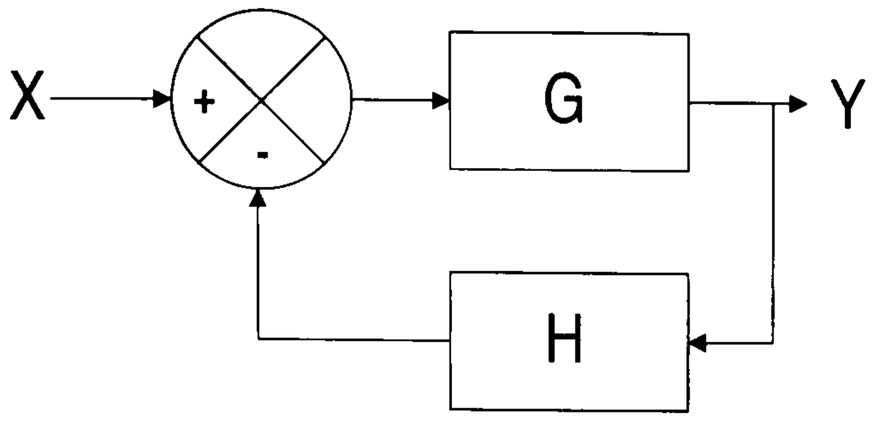
In practice design can often not be separated into the three distinct phases, as different design ideas are tested, even before the requirements are finalised. There is no absolute cut-off point, at which it can be said, that no more detail is required for a particular phase, and decisions made early on in the design phase may have a serious effect on the later stages.

Each of the design phases are of an iterative nature, as is indeed the whole design process. Furthermore, as the design becomes more detailed and as more and more decisions are being made, the difficulty and cost of changes increases [The Open University 1993]; thus making *correct* design decisions as early as possible is vital.

The iteration within the design phases and between the phases results in the design converging from a nebulous idea and an ill-defined problem through to a well-defined solution that, when manufactured, represents a specific object. Obviously this is not necessarily a straightforward process and periods of divergence and convergence will alternate within the overall convergent pattern of the design process. The main aim of the design process is to find an overall solution that is a good compromise between constraints[1] and requirements [The Open University 1993].

The aim of designing an object or a service is that it should fulfil intended *functional requirements* with the required degree of reliability and repeatability for at least its designed life. These requirements are part of the *external properties* and the designer can chose and manipulate the *internal properties* of the design to achieve the desired. This shows that the internal and external properties are inherently linked and that the quality of the internal properties is the cause for the external properties [Hubka 1989]. Internal properties of the design include design characteristics (technological

[1]Laws, regulations, financial limitations, material property limitations etc.



$$\frac{X}{Y} = \frac{G}{1+GH} \approx \frac{G}{GH} = H^{-1} \text{ for } GH \gg 1$$

Figure 2.1: Feedback control loop depicting the design process. Y is the desired output, X is the input, G is the *synthesis capability*, and H is the *analytical ability*. A large $G \times H$ helps the design process. The ability to judge the design process *quickly* helps the design process [Suh 1990]

principle, transformation operation, etc.), elementary design properties (arrangement of structure, element form, element materials, manufacturing method, etc.) and general design properties (strength, stiffness, wear, etc.). Thus by directly influencing the internal properties the designer indirectly influences the external properties such as economics (manufacturing cost, life-cycle cost, etc.), functions, operation (reliability, safety, etc.) and environmental impact properties.

An aspect of design is that it is *solution focused* and this differs markedly from the scientific *problem focused* approaches [Middendorf 1986, The Open University 1993]. A solution focused approach focuses on generating a satisfying solution, without necessarily understanding all the constraints and rules of the problem. An extreme of the solution focused approach is the so-called *'satisficing'* where the aim is to produce *anyone* from what is probably a large range of satisfactory solutions. A totally different approach, where a deeper understanding of the problem is required, would be to try to find the optimum solution of the large number of satisfactory solutions (optimising). Here design methodologies become important as their purpose is to find an optimum result for a design in a structured manner [Pighini, Long & Todaro 1989].

One way of illustrating the aforementioned iterative nature of design is shown in **Fig. 2.1** [Suh 1990]. It shows the design process as a feedback control loop.

Here the creative process G is aided by the analytical process H. This shows that any creative process must be checked through analysis and corrections of the perceived problems have to be taken to arrive at the proposed solution Y. From the control diagram it can be seen that the gain of the feedback loop has to be as large as possible to ensure fast convergence on the desired outcome. Therefore, if $G \times H$ is much larger than unity then the gain is approximately equal to $\frac{1}{H}$; i.e. this illustrates the importance

of being able to judge the quality of a design (H) as this aids and is even vital for the creative process (G) itself. Furthermore, it shows that without being able to judge the quality of a design it is difficult to rapidly generate the *best* design as a good design is not distinguished from a bad design. Concluding, this means that the design process is aided significantly by providing relevant information on the design, since this aids the analytical process H.

2.3 Design Objectives

Here some aspects concerned with the objectives of design are introduced. They all have in common that they are of importance and that the non-fulfilment of even one of these may lead to difficulties. Some design objectives may be summarised in the following:

BENEFIT CREATION is the benefit (mostly financial) that a company gains from making a product or providing a service.

PRODUCIBILITY describes the demand of whether it is possible to manufacture a product in accordance with the other main objectives.

FUNCTIONALITY describes whether or not a product or service fulfils the need it was designed for.

PERFORMANCE is linked to functionality but with an additional valuation criteria.

AESTHETICAL FORM cannot be achieved independently from other objectives and often results from seeking the simplest answer to a complex problem.

ERGONOMICS describe the performance with an emphasis on the human-machine interaction.

ADHERENCE TO STANDARDS AND LEGAL REQUIREMENTS form general guidelines which are not to be ignored and protects the producer against claims resulting from accidents during the product's manufacture and use.

SAFETY during use can be linked to performance and ergonomics with an emphasis on what measures are taken to protect the user from accidental misuse. Many safety requirements are laid out in the national standards and legal requirements.

In the following a few design methodologies with their dominant design objectives are introduced. It is not intended to disregard the above objectives, but with respect to this study the following are considered the most relevant.

2.3.1 Design for X (DfX)

The unifying thoughts behind Design for X [2] is to optimise the design with respect to X. This can often mean that decisions made with respect to X_1 might conflict with decisions of X_2 [Borg & MacCallum 1997]. This has lead to the view that all X's have to be considered concurrently in as efficient a fashion as possible. In a concurrent engineering environment the design is optimised in parallel from the various design points of view, i.e. from the fulfilment of the functional requirements to the manufacturability and production planning, from the maintainability to the optimisation of the end-of-life scenarios. The optimum result would be the minimisation of the impacts, cost and effort for the sum of all X's. In most cases this means to make compromises, since different design rules and methods may lead to contradicting conclusions.

An example that illustrates this is that both Design for Manufacture (DfM) and Design for Assembly (DfA) have as a main aim to minimise the cost of the product before it leaves the factory by making products production and assembly 'friendly' [Pighini *et al.* 1989]. These strategies do not include the whole life cycle and may lead to an increase of the total life cycle cost if, e.g., the DfA rules result in a design that is not maintainable — DfA rules often suggest to use one-way fasteners and that the number of separate components is reduced to minimum — and therefore has to be discarded as soon as the product or one part of it is damage. This shows that compromises between the various methods would be needed to achieve the best overall result. DfM and DfA are obviously important aspects of the design and a designer has to consider the details of manufacturing and assembly during all stages of the design work [Meerkamm, Finkenwirth & Räse 1989, Pighini *et al.* 1989], but other DfX rules must not be neglected.

A more holistic approach is the basis for Design for the Environment (DfE). DfE seeks to integrate product and process design into a single function to more effectively reduce aggregate environmental impacts [Keoleian & Menerey 1994].

2.3.2 Life Cycle Design (LCD)

As explained for DfE previously, LCD, too, is a holistic approach considering product and process design concurrently. Therefore DfE and LCD are considered different names for essentially the same approach, but DfE originates from the DfX approach while LCD is a further development from the concurrent design programmes [Keoleian & Menerey 1994].

[2] X can stand for manufactureability, assemblibility, disassemblibility, maintainability, the environment, etc.

LCD has to be differentiated with respect to LCA. LCA and related approaches on their own are evaluation tools, but not design methods. On the other hand LCA can be used in an iterative manner to evaluate design decisions, make changes to the design and to carry out another LCA. The drawback of this is that if the assessment is done at later stages of the design process where sufficient detail is available then any changes to the design could be costly in terms of time that is required to make the changes. If the iteration loop is not carried out for one particular design but for successive models of the design, i.e. the design is manufactured and used and the following models are changed to incorporate design changes due to the LCA, then the iteration loop is very long indeed and changes evolve over much longer time periods.

LCD strategies should also be founded on environmental stewardship which is incorporated in the overall business strategy. Environmental stewardship of products requires a company to extend corporate responsibility on the entire product life-cycle. According to Tipnis [1994] this forms part of a competitive strategy which also allows companies to 'compete on ecology'.

2.3.3 Process Planning and Sequencing

Aspects of process planning and process sequencing are include in advanced design procedures. With respect to life cycle approaches, these methods include ecological and economical considerations as a main feature for this category of planning. These methods do not include the consideration of the other life cycle stages except the manufacturing stage. This may be the most important part in a DfM and DfA approaches, but it is also important for the later stages in the design process in a life cycle design approach.

From the perspective of manufacturing, process planning and sequencing, as opposed to e.g. the detailed machining paths and setups required for an individual machine, involves the analysis of the importance of the manufacturing sequences on the overall manufacturing stage. Historically process planning was based primarily on minimising machining cost, but today the optimisation problems include flexibility, component quality and environmental impact. Including these aspects means, that they cannot be easily represented in terms of machining cost as many terms carry uncertainties, discontinuities and/or present difficulties in internalising cost [Sheng & Srinivasan 1995].

Process selection is the first step in process planning. This was addressed for the concept stage in the design process [Esawi 1994, Esawi & Ashby 1995, Esawi & Ashby 1996]. The method is based on a *screening* procedure where the process capabilities are displayed graphically in *Process Selection Charts*. During screening the processes which are not able to make the required part are excluded. The screening is followed by

a *ranking* procedure in which the ranking criteria is relative cost of the manufacturing processes.

2.4 Life Cycle Assessment

In this section life cycle assessment is discussed in general terms. It is not intended to summarise all the specific life cycle assessment methodologies developed in the past, since most methodologies include many of the aspects covered here. There is general agreement on how to obtain the life cycle inventory [Boustead 1992, Grahl 1996] and the main difference between specific life cycle assessment methodologies lies in the environmental impact assessment method utilised, which can be very different. Therefore some are described in more detail in Section 2.4.5.

2.4.1 Historical Overview

The first approaches, to what today is called life cycle assessment, were developed in the 60's. The studies of that time dealt mainly with energy issues [Boustead 1995], which was related to the general interest in the scarcity of raw materials and fossil fuels. Formalised LCA tools developed in the USA were mainly based on raw materials and energy analysis, such as the REPA method by [Hunt, Sellers & Franklin 1992]. The development of LCA procedures began in Europe in the early 80's, especially in Switzerland, where the Ministry of the Environment initiated research lead to the development of the 'Critical Volumes Method' and the 'Ecopoint method' [Habersatter 1991]. Several European research groups began publishing on LCA methods in the 90's, often supported by national agencies (e.g. CML classification method in the Netherlands by Heijungs et al. [1992], updated by Huijbregts [1999]), Environmental Priority Strategies (EPS) method in Sweden [Steen & Ryding 1994]). Related methods, such as the KEA method [VDI-Richtlinie 4600 1995] and Material Intensity Per Service-unit (MIPS) [Schmidt-Bleek 1997] were also developed in Europe. In the recent past the International Standards Organisation has issued a framework for conducting LCA's [ISO 14040 ff. 1997].

2.4.2 What is Life Cycle Assessment?

Life cycle analysis and life cycle assessment[3](LCA)[4] is the breakdown and investigation of the whole life of products and services with respect to environmental impacts of the various life cycle stages. The life cycle stages include the following major stages [Benda, Narayan & Sticklen 1993, Keoleian & Menerey 1993, Keoleian & Menerey 1994]:

1. Raw Materials Acquisition
2. Bulk Processing of Raw Materials
3. Product and Packaging Manufacture
4. Consumer Use
5. Retirement (Recycle, Compost, Remanufacture, Reuse)
6. Final Treatment and Disposal

Fig. 2.2 gives an overview of the life cycle system; it highlights the sequential nature of the individual life cycle stages for an individual product, but also shows how everything starts and ends at the earth, when considering our planet as a closed system. It can be seen that — to a lesser or greater extent — all life cycle stages have as inputs materials, energy and labour and as outputs they have have untreated and treated residuals (waste streams), whereby the treated residuals are disposed of in a controlled manner, while the fugitive waste reaches the biosphere untreated, representing a potential environmental hazard.

These stages have various importance in the whole life cycle and are dependent on a large number of variables, ranging from the usage patterns to the materials and processes used. Schaefer [1993] points out that the inclusion of all post-use scenarios have to be included in a complete LCA, i.e. re-use and recycling and the various disposal scenarios such as landfill, high temperature incineration for hazardous waste treatment and incineration with energy recovery. Furthermore it is pointed out that the inherent energy of raw materials (e.g. oil for the polymer manufacture), semiproducts (such as polymer granules) and the non-energetically used consumables (e.g. cooling oil) must be included in the energy analysis [Schaefer 1993]. Nothing should be counted twice, so that the thermodynamic law of conservation of energy is obeyed.

[3]If the two are to be distinguished then Life Cycle Analysis is the analysis of the flow of material (incl. waste and pollutants) and energy flow for products and services over the whole life cycle, while an additional Environmental Impact Assessment (EIA) and Improvement Phase is required for Life Cycle Assessment

[4]Here LCA always means Life Cycle Assessment.

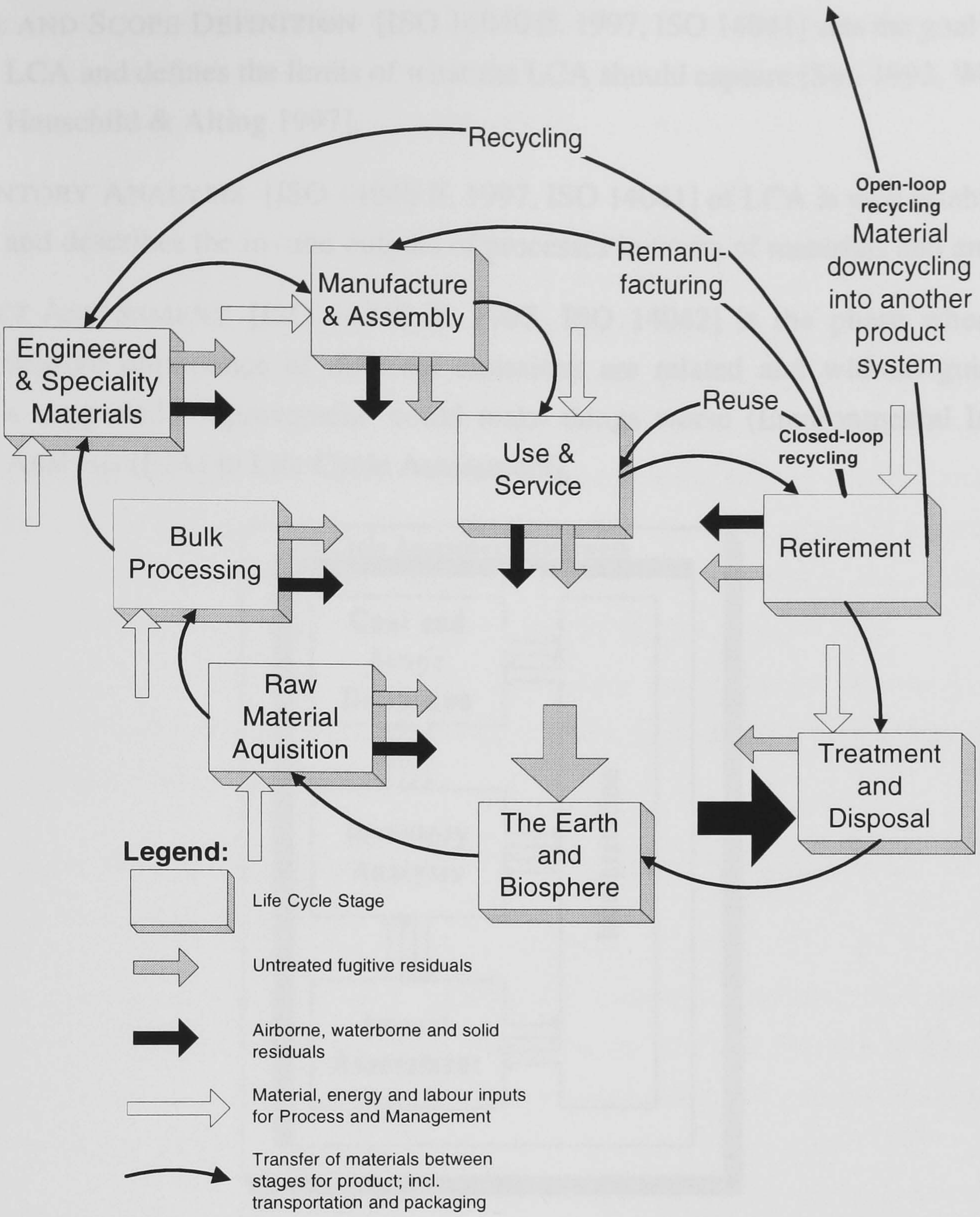


Figure 2.2: The life cycle system (adapted from [Keoleian & Menerey 1993, Keoleian & Menerey 1994])

LCA has become more important with the recognition that the production and consumption of manufactured products and the provision and use of services has an effect on resources and the environment. Consequentially it is essential to consider the final overall state when designing a product or service. In addition to LCA being seen as a way to identify 'weak' points of a design, one argument is that LCA will be required in the near future for every product and process, either due to government regulations or due to the market forces, i.e. the consumer [Benda *et al.* 1993]. This is accompanied by the requirements to develop more energy efficient products, technologies for disassembly, re-manufacturing and recycling [Tipnis 1994].

For a complete life cycle assessment the analyst has to iterate between the following phases (see also **Fig. 2.3**)

GOAL AND SCOPE DEFINITION [ISO 14040 ff. 1997, ISO 14041] sets the goal of the LCA and defines the limits of what the LCA should capture [Sou 1993, Wenzel, Hauschild & Alting 1997].

INVENTORY ANALYSIS [ISO 14040 ff. 1997, ISO 14041] of LCA is well established and describes the in- and outputs of processes in terms of materials and energy.

IMPACT ASSESSMENT [ISO 14040 ff. 1997, ISO 14042] is the phase where the relative importance of different emissions are related and without guidance a suggested 'improvement' could make things worse (Environmental Impact Analysis (EIA) in Life Cycle Assessment).

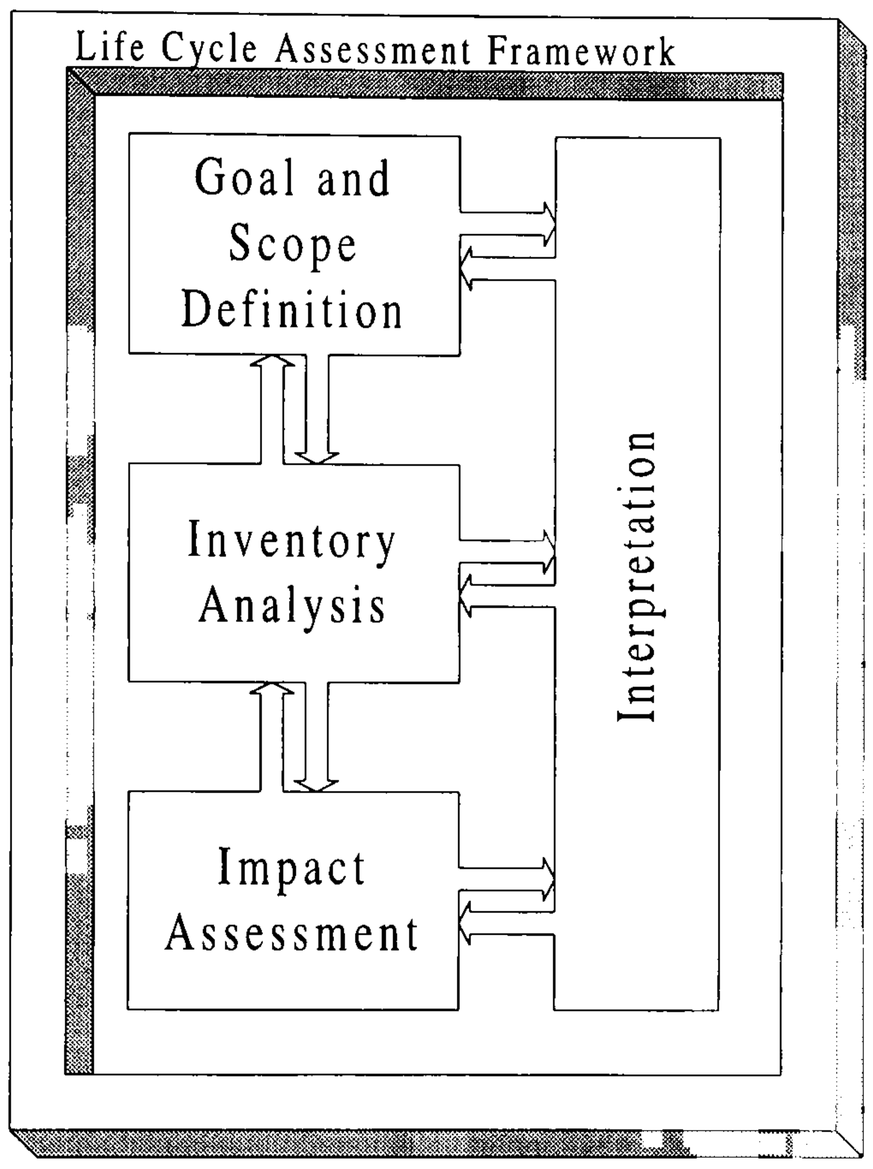


Figure 2.3: The LCA Framework according to ISO 14040 (adapted from [ISO 14040 ff. 1997])

To carry out a full LCA on even a simple product means that the analyst has to gather information on all the processes that the product and any parts of it comes into direct and indirect contact with. But the complexity of full LCA's usually limits studies to scientific bodies or to large industrial companies [Grahl 1996]. It is therefore important for LCA's to become more widespread, to develop simplified LCA methods, such as streamlined LCA approaches. Streamlined LCA's could be used as a guide to industry, government and consumers with respect to choice [White & Shapiro 1993].

As mentioned, the complexity of the interactions leads quickly to a vast amount of data that has to be organised, verified and analysed. The advantage of software tools to support the aforementioned becomes quickly apparent.

One problem of LCA is the lack of a so-called 'LCA-currency' (see also Section 2.4.6). It is argued that an ecological evaluation cannot be represented in the form of just one

characteristic number, because not all the effects of human activity are known and some facts can only be presented in technical and physical units, while others can only be expressed in monetary terms [Schaefer 1993].

Why carry out LCAs? The aims are varied and depend on the application of LCA. In product development the aim is an increased overall product performance in terms of reduced material requirement, energy requirement and emissions associated with the life cycle of the product. In strategy planning LCA is used to evaluate the effect strategic decisions may have. Strategic decisions evaluated may include the construction of internal recycling facilities or take back strategies for existing products. In public policy making government offices may use LCA results as part of a process to justify taxes on certain emissions. Marketing departments may use LCAs to illustrate the 'environmental superiority' of a product, usually shown by eco-labels.

Environmental considerations often reveal economic improvement options [Saur & Finkbeiner 1997] and a more general but descriptive point was put forward by Frosch & Gallopoulos [1989] who said that

> "economical and environmental goals are the same: bad places to live do not make for good markets."

A more specific case showed how substituting materials (solvents) and processes resulted in a ca. 75% reduction of hazardous waste and that the use of hazardous materials can mean a 10× cost penalty over implementing and using non-hazardous materials [Baca 1993].

2.4.3 Goal and Scope Definition

Goal and scope definition involves the outlining of relevant information on the study. The scope of the LCA study defines the breadth and depth of the inherent detail in which the study is carried out. The study's scope relates to the study goal, by illustrating that the scope is sufficient to address the study goal. It includes

- goal (objective of LCA, sponsor, intended audience)
- scope (function of system, life cycle phases covered, system boundaries, allocation procedures, assumptions, limitations)
- level of detail (depth (vertical completeness), cut-off thresholds for inventory)
- spatial and temporal scale (region and date (year) for which LCA is conducted)
- accuracy and precision (reliability of data sources)

- interpretation (method of environmental impact assessment utilised)

Some objectives of an LCA study are :

- increase product performance (reduced use of raw materials, reduced emission level, compliance with regulations);
- assessment of existing product's performance in terms of environmental impacts;
- assessment of new products in terms of environmental impacts;
- evaluate alternative options (road or rail transport; fossil fuels or renewable energy sources, etc.);
- evaluate the need to introduce new equipment to achieve an increased performance of a system in terms of environmental impacts;
- apply for an eco-label.

An emphasis of this phase is the aim to reduce the misuse of results of LCA's as a marketing weapon by highlighting certain aspects of the life cycle and hiding others. Therefore the goal definition should include information on sponsors and the overall objective of the LCA [Sou 1993, Wenzel *et al.* 1997].

2.4.4 Inventory Analysis (LCI)

Inventory analysis (also termed Life Cycle Inventory [LCI]) is the most widely accepted of the phases [Boustead 1992, Grahl 1996]. It provides a detailed picture of raw materials and energy inputs used by a system and of the solid, liquid and gaseous wastes produced as outputs [Sou 1993]. To give a impression of the scale associated with compiling an LCI, Bretz [1998] estimated that an analyst may require some 10^4 to 10^5 or more numerical data elements for a complex product which will consist of thousands of unit processes.

The inventory of relevant information on processes requires the inclusion of unit data and the setting up of unit processes. The inventory should include the environmental exchanges from the complete product system or for parts thereof and the data should be presented in a transparent form so that it is useful to the analyst [Wenzel *et al.* 1997].

Data representation must be kept in a uniform format that is descriptive for all described processes. Usually information of LCI's include

1. information on the process itself
2. an inventory of the inputs and outputs of the process

3. a characterisation of the information, i.e. the origin and quality of the data and the boundary conditions of the process.

A general approach to all LCI's is depicted in **Fig. 2.4**, where all real processes have in common — to a lesser or greater extend — that they have as *inputs*

- Materials and
- Energy (includes fuel),

and as *outputs*

- 'Products' (e.g. engineering material, fuels, electric energy, engineering machine elements, consumer products) and
- Waste (solid, liquid and gaseous emissions and waste energy, usually as heat).

This information can be gathered from an analysis of all the processes and a complete picture of a life cycle of a product is achieved by creating a network describing the in– and outputs of the the individual processes and their relationship.

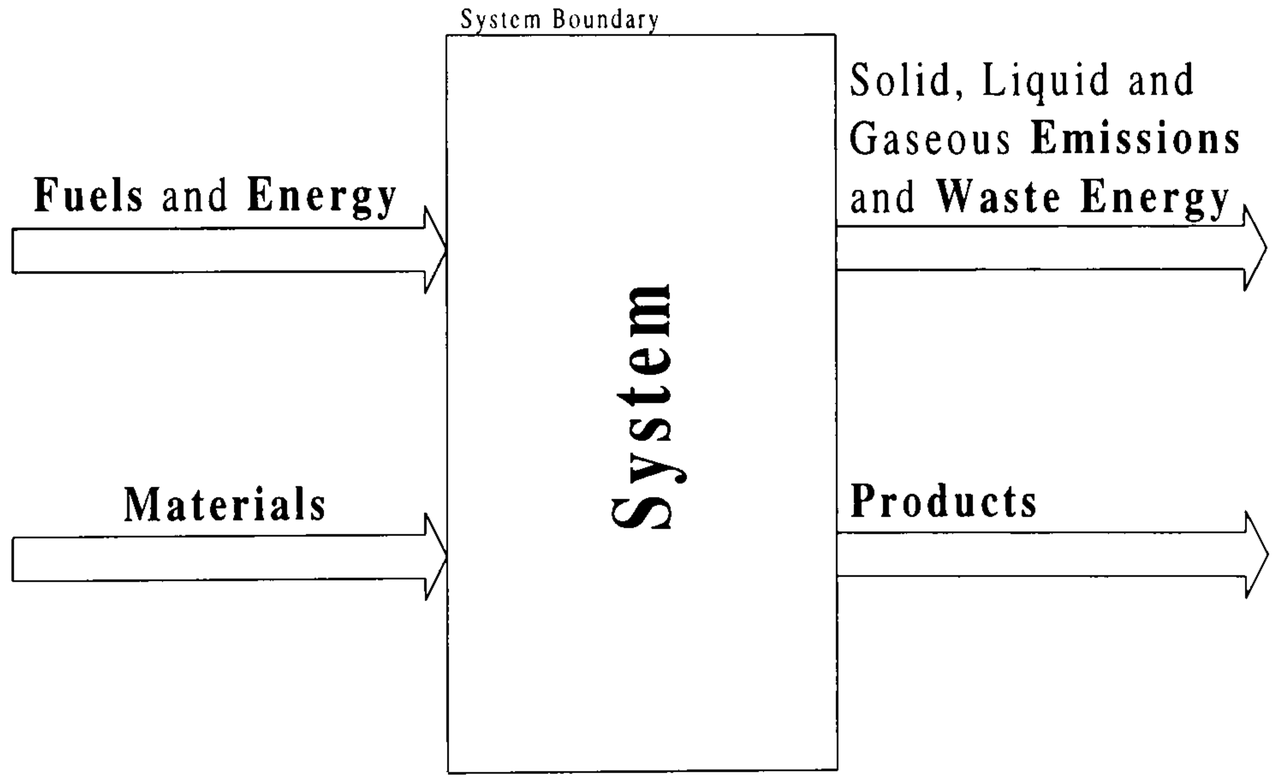


Figure 2.4: Schematic of the inputs and outputs of a system

Most of the LCI methods assume that the material flows throughout the processes are static and dynamic effects due to process degeneration, process improvement, reliability characteristics, a product's seasonal nature, etc. are neglected. This approach is sufficient for many situations such as mass-production where the demand remains constant over a considerable time [Jackson & Wallace 1997]. The LCI methods described in the following neglect or average out the aforementioned dynamic effects.

The following description focuses on the main methods used to varying degrees when determining the LCI.

Using terms from cost assessment methods, the inventory methods can be divided into micro analyses ('bottom-up' approaches) and macro analyses ('top-down' approaches). The bottom-up approaches of the inventory look at the inputs, outputs and waste streams of *each* process step in detail that occurs in the life cycle. The inventory is determined by adding up the inventories of the individual processes (hence 'bottom-up'). The most common micro analysis is the detailed analysis of a process chain (Process Chain Analysis).

The top-down approaches analyse the inventory on a larger scale. Here a system is defined to include several processes (the order of scale can be from a single manufacturing line, to a whole factory, or even a whole country or region), where the inputs and outputs to and from the individual processes are summarised for the whole system. In cases where there are more than one product output by the system, the inputs and waste streams have to be allocated to the product in physically sensible manner. The inventory is determined by selecting a specific product quantity (e.g. number of products, mass of product) and allocating the proportion of the inputs and outputs associated with the specific product quantity (hence 'top-down' as first the overall inventory of a system is determined and then allocated to products of the system).

Process Chain Analysis (PCA)[5] In the analysis of process chains a complex process is subdivided into a number of small processes which individually can be easily overseen [Boustead & Hancock 1979, Wagner 1978]. These processes are analysed with respect to their relevant in- and outputs. At the end of a process chain — representing a complex process — lies the final product. The process chain then includes all the pre-required and therefore accumulated entities. These entities can be of different nature; the most used are energy, materials and various waste streams (emissions).

ADVANTAGES The inventory associated with a product can be determined more exactly compared to other methods, since it is based on the physically existing process chain for a particular product. Therefore results of a product inventory determined as whole according to this method allow a confident comparison between different products [Wagner 1978].

DISADVANTAGES The main disadvantage of the process chain analysis is that it entails the collection of a large number of data [Wagner 1978]. On the other hand this has been partly reduced by the use of computational tools. The analysis still requires a large amount of time and work, even though the process chain can be truncated at the second order [Boustead & Hancock 1979, Wagner 1978] (see also Section 2.5.3 on p. 49).

[5] in German Prozeßkettenanalyse

Input-Output Methods Process chain analysis focuses on individual processes. In many cases this level of detail is unpractical and the aggregation of several processes into a single system simplifies the determination of the inventory. The system's boundary conditions need to be specified and the waste streams and inputs require allocation to the products (see Section 2.5.4, p. 50, for details).

Depending on the size of the system, the data is collected over a specific period of time. In cases where the system is relatively small (such as a number of machine tools in a production cell or a complete production line) the data can be collected for a specified number of products produced. The time of collecting data can range from hours to weeks. In larger systems (such as whole factories) the inventory is usually determined from data associated to collected financial data (such as from material purchases, waste disposal costs, energy purchases, product sales). As this type of data is usually determined for financial years, the inventory is an average over a year. Similar periods apply to a system which describes a geographical region.

ADVANTAGES The systems size can be chosen to suit the required level of detail required for the inventory. This leads to substantial reduction in the amount of data, that needs to be collected. The specific inventory of a product represents an average for a system.

Depending on the time scale over which the data is collected, the method inherently averages out temporal differences, due to influences such as seasonal variations, production start-up periods, etc..

This method is therefore suitable when an average inventory of a product from a specific system is of interest.

DISADVANTAGES A disadvantage of this method is that, depending on the size of the system, assumptions (e.g. on allocation) have to be made.

The inventory does not detailing the inputs and outputs of the individual processes within the system.

Depending on the size of the system, the data may be out-of-date, as e.g. companies require months to determine a previous years data.

Input-Output Method Using Financial Correlation This type of analysis can be used to determine estimates of the average LCI of raw materials, some engineering materials and energy generation for geographical regions.

The input-output method is extensively used for macro-economical analysis, i.e. the financial interaction of industrial sectors is investigated. It has also been adapted to analyse energy consumption patterns of industrial sectors [Wagner 1978]. This is discussed in the following.

The method relies on correlating financial interactions of industrial sectors and the energy production and usage of industries.

The Input-Output-Tables describe the financial interactions of industrial sectors in a given time and for a specific region. These tables are based on national statistics and can therefore only be obtained for past periods

The Input-Output-Tables and the energy statistics must each describe the same geographic region[6] and time[7] period.

ADVANTAGES For the Input-Output method using financial correlations the investigator requires only two inherently consistent statistics, which are the Input-Output-Tables describing the financial interaction of industrial sectors and the energy statistics relating a region's primary energy consumption and production, the energy conversion and the secondary energy consumption and production [Wagner 1978]. Also these statistics exist for a wide range of technologies and industries as they are often used in macro economic calculations. Therefore an analysis can be carried out relatively easy and relatively fast. Also, this method can be used in the cases where a part or product is representative for one or more sectors. This is usually true for large products such as whole power stations, as it includes nearly all the products that are made in the electrical engineering sector [Wagner 1978].

DISADVANTAGES A disadvantage of this method is that many assumptions have to be made which are difficult to make clear to the end-user of the data. These assumptions also require a relatively large amount of work for a researcher to follow the assumptions[8].

A further difficulty is the boundary definition for the industrial sectors used in the input-output tables [Wagner 1978]. An Example is that the non-ferrous-metal industry includes both the copper and aluminium production. These are from an LCA point of view two very different branches.

The final disadvantage is that due to the time of the publication of the statistical tables the data is usually out-of-date by about 3 to 4 years [Wagner 1978].

2.4.5 Environmental Impact Analysis (EIA)

The impact analysis involves the linking of the inventory inputs and outputs to real world environmental problems. This is often controversial, since many effects depend

[6]Usually a country.

[7]Usually a financial year.

[8]The assumptions include such things as how to evaluate the imported energy and goods, or how to weigh local combined heat and power plants for a hole region.

on the concentration of the emissions. Various methods for impact analysis have been proposed.

The EIA methods can be categorised into the methodologies that attempt to measure actual impacts, while other methodologies are based on predicting potential impacts.

Impact assessment criteria can be categorized into three main groups [Wenzel *et al.* 1997]:

1. environmental impacts
2. resource consumption
3. impacts on the working environment

According to the recommendations of SETAC [Fava, Denison, Jones, Curran, Vigon, Selke & Barnum 1990] and ISO 14040 ff. [1997] an EIA should comprise of

1. Determination of the relative contribution of the pollutant to the various types of environmental impacts.
2. Normalization of the potentials with respect to e.g. the impacts of the society as a whole, i.e. this is used as an indication whether or not the impact is large or small.
3. Weighting the potential impacts to determine the most important.

The process of normalising and assigning weights is in a sense converting the different units of the inventory into the same units. But in most evaluation schemes the weighting especially relies on the (often subjective) judgement of the evaluator being consistent [Fu & Cebon 1997].

To illustrate the diversity of environmental impact assessment methods the following summarises some EIA methods.

2.4.5.1 The EIA of Kaebernick & Paul [1995]

In this approach the pollutants are ranked according to the

- effects of the pollutants and the
- risks of exposure.

Furthermore the effects of the pollutants[9] are graded according to the

[9]Ranking pollutants according to the relative toxicity and therefore their effect is a far from perfect attempt to address this problem [White & Shapiro 1993].

- mortality of organisms[10] due to acute exposure
- mortality of organisms due to chronic exposure
- sublethal impairment of various aspects of physiology and morphology
- measurable biochemical or behavioral effects

The risk of exposure is graded according to how often expected concentration levels exceed a certain threshold level. Therefore

$$\text{Score of Pollutant} = \sum_{i=1}^{n} (\text{Grade of Effect})_i \times (\text{Grade of Risk})_i \qquad (2.1)$$

where n is the number of dose effects. In many cases pollutants are similar so that they can be grouped together. Then

$$\text{Score of Group} = \frac{1}{m} \times \sum_{k=1}^{m} \left[\sum_{i=1}^{n} (\text{Grade of Effect})_i \times (\text{Grade of Risk})_i \right]_k \qquad (2.2)$$

where m is the number of members in the group.

The conclusion of the study is that lead receives the highest score because it is both highly toxic and widely distributed in the environment. SO_x and NO_x are less toxic, but they rank relatively high due to their wide distribution.

2.4.5.2 The EIA of the EDIP Method [Wenzel *et al.* 1997, Wenzel & Hauschild 1997]

Similar to the previous method this method defines the

$$\sum \text{Impact Potential} = \sum [(\text{Quantity of substance}) \times (\text{Substance's impact potential})] \qquad (2.3)$$

The EDIP method looks at the potential contribution to a type of environmental impact. The types of environmental impact are shown in **Tab. 2.1**.

As can be seen from the table the method defines the categories for the environmental impact at the early stage of the cause-effect chain[11] as it is not possible to predict the actual effects and consequences. Furthermore the substances are assessed according to all their contributions to several environmental impacts[12].

[10] These include organims from the plant and animal kingdom and humans.

[11] E.g. acidification and not a later effect of, say, weakened growth of trees or toxic impact on fish.

[12] E.g. NO_x contributes to acidification, nutrient enrichment, photochemical ozone formation and toxicity to humans via the atmosphere.

Table 2.1: The EDIP method's assessment criteria [adaped from [Wenzel *et al.* 1997]]

	Environmental	**Resources**	**Working Environment**
Global	Global Warming [gw] Stratospheric ozone depletion [so]	Fossil fuel (e.g. Oil, coal, natural Gas) Metals (e.g.FE, Al, Cu, Zn, Ni, Cr, Mn,Ag and Au) Other minerals (e.g. limestone, phosphate,salt)	
Regional	Photochemical ozone formation [po] Acidification [ac] Nutrient enrichment [ne] Persistent Toxicity [pt] (Human toxicity from the water and soil compartment Chronic ecotoxicity in the water and soil compartment)		
Local	Ecotoxicity [et] (acute ecotoxicity in the water compartment) Human toxicity [ht] (human toxicity from air compartment) Land filling (bulk waste [non-hazardous], hazardous waste, slag and ashes, nuclear waste)	Biomass (e.g. wood, straw, grain) Water (ground water, surface water) Others	Cancer due to chemical substances Allergy due to chemical substances Damage to reproductive system due to chemical substance Damage to the nervous system due to chemical substance Musculoskeletal injuries due to monotonous repetitive work Hearing impairment due to noise Grievous bodily harm due to accidents

The calculations of the EDIP EIA method can be summed up by saying that the 'emissions potential' [EP] of the substance i with respect to the environmental impact j is the product of the 'equivalence factor' [EF] and the magnitude [Q], i.e.

$$EP(j)_i = Q_i \cdot EF(j)_i \tag{2.4}$$

The environmental impacts j are listed in **Tab. 2.1** where the abbreviations are given in the square brackets. The total emissions potential for one environmental impact j is the sum for all the substances i, so

$$EP(j) = \sum_i EP(j)_i \tag{2.5}$$

Furthermore the method includes site factors [SF] where the knowledge of *site-specific considerations* for a process p is included. The magnitude of SF reflects the

way the emissions occur and the sensitivity of the environment where they occur. If the site-specific contributions are unreasonable then $SF = 0$ and if on the other hand no information on site-specific conditions is available then $SF = 1$, which represents a conservative viewpoint. Therefore EP becomes

$$EP(j) = \sum_p \sum_i EP(j)_{p,i} = \sum_p \sum_i (Q_{i,p} \cdot EF(j)_i \cdot SF(j)_p) \tag{2.6}$$

The site factors is related to the environmental impact category j and to the individual process p but not to the substance i. Also, as can be seen in **Eq. (2.6)** that for each process p the contributions of the substances i are calculated first for each impact category j and then the impact potentials are summed up for all the processes p.

The *resource consumption* RC is dealt with in a simple manner as can be seen

$$RC(j) = Q_i \tag{2.7}$$

Therefore the resource consumption is just the summarised quantity of the resources, Q_i.

Similarly the *potentials for impacts on the working environment* WP are measured as the duration of the impact Q_i within each of the seven categories j

$$WP(j) = Q_i \tag{2.8}$$

The **normalisation** of EP, RC and WP is carried by dividing the actual by a normalisation reference. This reference value is the ratio of *the resource consumption and potential impacts which society imposes on the environment and working environment each year for the area in question in the reference year* to the *population of the inventoried area*. The dimensions of the normalisation references *impact potential per person per year*. Therefore the dimensions of the normalised impact potentials are expressed in *person-equivalents* [PE], i.e. fractions of the contribution to the impact deriving from the average person.

$$NEP(j) = \frac{EP(j)}{T \cdot ER(j)_{90}} \tag{2.9}$$

$$NR(j) = \frac{RC(j)}{T \cdot RR(j)_{90}} \tag{2.10}$$

$$NWP(j) = \frac{WP(j)}{T \cdot WR(j)_{90}} \tag{2.11}$$

where T is the duration of the service defined in the functional unit[13], $ER(j)$ is the reference value for the emissions potential in 1990, $RR(j)$ is the annual resource consumption of the resource in 1990 and $WR(j)$ is the exposure time of the impact

[13] I.e. the designed or anticipated operating or working life of a product.

per employee per year within each individual impact category[14] for the years around 1990.

The **weighting** of the impacts is done by multiplying the normalised impact potential with a *weighting factor* WF. Therefore

$$WEP(j) = WF(j)_{EP} \cdot NEP(j) = WF(j)_{EP} \cdot \frac{EP(j)}{T \cdot ER(j)_{90}} \tag{2.12}$$

so that WEP represents a person-equivalent value corresponding to a target value for a year, i.e. PET_{W2000} is the person-equivalent based on the target values for the world in the year 2000;

$$WR(j) = WF(j)_{R} \cdot NR(j) = WF(j)_{R} \cdot \frac{RC(j)}{T \cdot RR(j)_{90}} \tag{2.13}$$

where WR represents a person-reserve value, i.e. PR_{W90} is the person-reserve for the world based on known reserves in 1990[15];

$$WWP(j) = WF(j)_{WP} \cdot NWP(j) = WF(j)_{WP} \cdot \frac{WP(j)}{T \cdot WR(j)_{90}} \tag{2.14}$$

where WWP represents a *reported work injury*, i.e. RWI_{DK90} represents the reported work injuries in Denmark in 1990 or in the years preceding 1990 for long term effects such as cancer.

The third term of **Eq. (2.12)** to **Eq. (2.14)** is arrived at by simply substituting **Eq. (2.9)** to **Eq. (2.11)** into the middle expressions respectively.

The weighting factors $WF(j)$ are defined as follows

$$WF(j)_{EP} = \frac{\text{Environmental impact potential of emmisions in 1990}}{\begin{array}{c}\text{Environmental impact potential of target} \\ \text{emissions for, say, the year 2000}\end{array}} \tag{2.15}$$

$$WF(j)_{R} = \frac{1}{\text{Supply horizon for resource (j)}} \tag{2.16}$$

where the supply horizon is defined as how long the known reserves will last for the current global consumption. This is obviously different for non-renewable resources, renewable resources where the demand exceeds the rate of regeneration and renewable resources where the demand does not exceeds the rate of regeneration.

$$WF(j)_{WP} = \frac{\begin{array}{c}\text{Reported injuries for impact category (j)} \\ \text{per annum in the region}\end{array}}{\begin{array}{c}\text{Total annual time for exposure to the impact} \\ \text{category (j) in the region}\end{array}} \tag{2.17}$$

[14] This is done only for Denmark.

[15] Therefore 20 mPR_{W90} would mean that if one person bought 50 products of the relevant type then the *ration* of known reserves has been totally exploited for a person today and is therefore not available for future generations.

This short summary has shown the complexity of a full EIA. A large amount of detailed data is required, which can often not be supplied with the necessary accuracy. Furthermore many effects are not known for sure and this may mean that especially long term effects are not taken into account. But this method is a very comprehensive method which has a lot of useful aspects that are worth noting.

2.4.5.3 The EIA method of BUWAL

The Swiss EIA method was developed for the Swiss Ministry of the Environment (BUWAL) in 1990 [Ahbe, Braunschweig & Müller-Wenk 1990, Habersatter 1991]. Annual environmental load limits are set by national environmental regulations. The load limits are used to determine an index from the actual flow of emissions streams in a geographical area. These indexes are then multiplied with the emissions and used resources to give a normalised and weighed result. The result was in so-called *Ökopunkte* (Ecopoints) as units.

The load limits are based on political decisions and they express the compromise between what is economically feasible and what is desirable.

2.4.5.4 The EIA method of the EcoIndicator '95

The Dutch EcoIndicator '95 is, similarly to the method of BUWAL, based on environmental load limits, but it is adapted to the load limits of Europe as a whole and they are not determined in a political manner as in the BUWAL method, but on scientific information [Goedkoop, Demmers & Collignon 1996].

The EcoIndicator '95 is based on an inhabitant equivalent for comparing different impacts, i.e. the **normalisation** is based on the environmental effects that an average European causes in a year. Thus, the outcome is that the environmental effect of the product is presented as a fraction of the total that an average person in Europe creates. The normalisation factors for the Dutch territory, Dutch consumption and West European Territory are listed in **Tab. 2.2**.

The difficulty of comparing health complaints of humans due to impacts and negative environmental changes due to impacts is overcome by **weighting** which is achieved by setting the target level for each effect so that it *yields a uniformly serious damage*, whereby the following damage levels are assumed to be equivalent [Goedkoop 1995]:

- The number of fatalities as a consequence of environmental effects. The level chosen as acceptable is 1 fatality per million inhabitants per year.

Table 2.2: Normalisation factors[a] (EcoIndicator'95)

Class	**Unit**	**Dutch Territory around 1993/1994**	**Uncertainty Dutch territory[b]**	**Dutch consumption around 1993/1994**	**West European territory 1990-1994**
enhancement of the greenhouse effect	kg of CO_2-eq/a	2.1E+11	S	1.4E+11	4.2E+12
depletion of the ozone layer	kg of CFC11-eq/a	4.4E+06	M	2.6E+06	5.6E+07
photochemical smog formation	kg of ethane-eq/a	1.9E+08	M	1.3E+08	6.3E+09
acidification	kg SO_2eq/a	9.2E+08	S	5.4E+08	3.4E+10
nutrification	kg PO_4eq/a	1.1E+09	S	5.4E+08	8.6 to 23.0E+09
human toxicity	kg HC-eq/a	8.8E+08	C	6.1E+08	3.9E+10
aquatic eco-toxicity	m^3 ECA/a	8.9E+12	C	5.1E+12	4.4E+14
terrestrial eco-toxicity low[c]	kg ECT/a	1.2E+13	C	8.0E+12	2.3E+14
terrestrial eco-toxicity high[d]	kg ECT/a	1.4E+14	C	5.6E+13	2.5E+16
abiotic depletion	1/a	6.6E–03	S	5.6E–03	—
energy use Low Heating Value	MJ/a	2.9E+12	S	1.8E+12	5.8E+13
energy use High Heating Value	MJ/a	3.1E+12	S	2.0E+12	6.1E+13
solid waste to be dumped[e]	kg/a	8.8E+09	S	14E+09	9.7 to 54.0E+10

[a] The latest normalisation data for the Netherlands and Europe are taken from http://www.pre.nl/normal.html, updated on 9 June 1998

[b] S(mall) ± 2.5%,M(oderate) ≥-50% and ≤+100%,C(onsiderable) <-50% and >+100%

[c] The low value is based on the assumption that the agricultural soil must be considered as part of the economic system, meaning that no the contribution of pesticide emission to terrestrial eco-toxicity is not considered (i.e. an underestimate.)

[d] The high value is based on the assumption that the agricultural soil is part of the environmental system and that all pesticide-use results in emission to the soil, excluded that part which is released to water (approx. 1%). This can be considered an overestimate.

[e] The reduction in weight due to the degradation of organic material is not included.

- The number of people who become ill as a consequence of environmental effects. This refers in particular to winter and summer smog. The acceptable level set is that smog periods should hardly ever occur again.

- Ecosystem degradation. A target level has been chosen at which 'only' 5% ecosystem degradation will still occur over several decades.

It is pointed out that this valuation is a subjective choice and cannot be scientifically based, but is based on assumptions and by changing the assumptions the weighting may change. In **Fig. 2.5** the principle for the weighting is briefly illustrated. In **Tab. 2.3** the actual weighting values are listed.

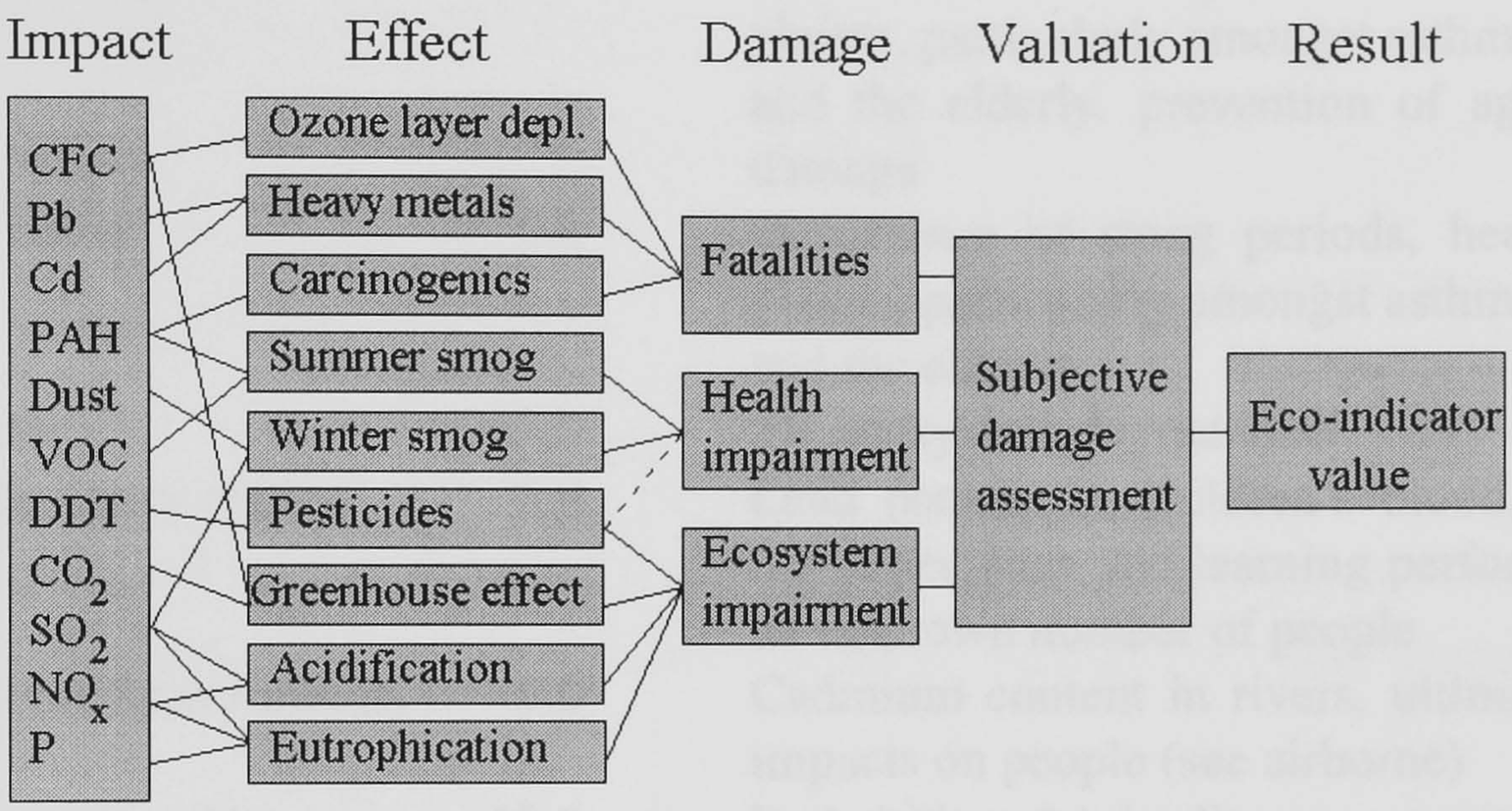


Figure 2.5: EcoIndicator weighting principle [Goedkoop *et al.* 1996]

This short introduction to the EIA of the EcoIndicator'95 has shown how difficult it is to make an objective evaluation. Since the weighting procedure is subjective and the normalisation procedure requires a large amount of data, of which a considerable amount is uncertain, it can be said, that this method lacks, to some extent, credibility.

2.4.5.5 The EIA of Sheng and Srinivasan [Sheng & Srinivasan 1995]

This impact assessment method is an assessment of effects on the Working Environment and is mainly aimed to be used in conjunction with process planning and not as a life cycle EIA. But the approach is interesting and it is therefore included here as it could be modified for a full EIA method.

The method is based on defining a 1×7 *Hazard Vector* $\mathbf{H}$ which is based on the dose-response of the constituents of each waste stream to the effect of

1. Oral Toxicity (O)

2. Inhalation Toxicity (I)

Table 2.3: Weighting factors (EcoIndicator'95) and the criteria applied to determine the factor [Goedkoop *et al.* 1996]

Environmental effect	**Weighting factor**	**Criterion**
Greenhouse effect	2.5	0.1°C rise every 10 years, 5% ecosystem degradation
Ozone layer depletion	100.0	Probability of 1 fatality per year per million inhabitants
Acidification	10.0	5% ecosystem degradation
Eutrophication	5.0	Rivers and lakes, degradation of an unknown number of aquatic ecosystems (5% degradation)
Summer smog	2.5	Occurrence of smog periods, health complaints, particularly amongst asthma patients and the elderly, prevention of agricultural damage
Winter smog	5.0	Occurrence of smog periods, health complaints, particularly amongst asthma patients and the elderly
Pesticides	25.0	5% ecosystem degradation
Airborne heavy metals	5.0	Lead content in children's blood, reduced life expectancy and learning performance in an unknown number of people
Waterborne heavy metals	5.0	Cadmium content in rivers, ultimately also impacts on people (see airborne)
Carcinogenic substances	10.0	Probability of 1 fatality per year per million people

3. Carcinogenicity (C)
4. Reactivity (R)
5. Flammability (F)
6. Eye Irritation (E)
7. Dermal Irritation (D)

The environmental effects are limited to the immediate exposures to waste streams in the vicinity of the processes, chronic effects such as soil contamination and atmospheric or waterborne releases to the environment outside the plant are not considered. This is acceptable as it is only intended to look at the immediate hazard to humans at their work environment and not to the overall environmental impacts.

The highly qualitative information of the site specific effects on health hazard is quantified using the Analytical Hierarchy Process (AHP)[16]. The site specific prioritisation matrix (AHP matrix) X is a square matrix relating the relative importance

of the health effects to each other. Next a rank value R_i is determined for each row i of $\mathbf{H}$, i.e. for each health effect.

$$R_i = \left(\prod_{j=1}^{k} X_{ij} \right)^{\frac{1}{k}} \tag{2.18}$$

where j is the column, k is the total number of columns and X_{ij} is the element in the AHP matrix.

A site specific vector $\mathbf{F}$ is determined by simple normalisation of R:

$$F_i = \frac{R_i}{\sum_{i=1}^{k} R_i}, \; i = 1 \ldots k \tag{2.19}$$

Finally the health hazard score (HHS) is calculated as

$$HHS = \mathbf{H} \cdot \mathbf{F} \tag{2.20}$$

This is then used to calculate a total weighted mass m_w of the waste streams

$$m_w = \sum_{i=1}^{n} (1 + HHS_i)\, m_i \tag{2.21}$$

The health hazard score is thus used to determine the relative importance of the various flows and this is then used to determine the weighed mass of the waste streams.

2.4.5.6 Interpretation of EIA results

The values determined from the environmental impact assessment are used as a guide to decision making in the improvement phases.

The aim is often a relative improvement of a future generation product compared to the current generation. The results from the EIA may highlight problem areas of the current product generation and the analyst can select alternatives (e.g. materials, production method) which result in an overall improvement with respect to the measures used in the EIA.

When comparing products, materials or processes 'improvement' means the selection of the 'superior' product, material or process with respect to the measures used in the EIA.

This highlights that the EIA method utilised will have a significant influence on the suggested improvement and there can be very different outcomes, as to what is 'improvement', when comparing the results from different EIAs of the same inventory.

[16] AHP is based on the pairwise comparison of decision elements with respect to a common criterion. AHP results in a hierarchical structure based on goals, criteria, sub-criteria and alternatives. The goals and criteria are weighed subjectively and from this a relative importance can be determined for the alternatives. This relative importance represents in this case the site specific effects on health hazard.

2.4.6 Common Problems of LCA's[17]

In the following the problems are listed that are encountered when carrying out LCA's [Benda *et al.* 1993].

DATA LIMITATION is due to the unavailability of data, but reliable information is essential for most correct and up-to-date[18] LCA's. This is one of the most common causes for uncertainty when conducting LCA's. One view is to only rely on published data for reproducibility [White & Shapiro 1993].

ASSUMPTIONS can be problematic where quantitative data are not known, i.e. when guesses have to be made.

STANDARDISATION is one of the greatest difficulties in LCA, and therefore it can be used by marketing people to their advantage, e.g. as a 'marketing weapon' a non-standardised LCA can show whatever one wants it to show. On the other hand it is argued that there is an established methodology for at least the inventory phase [Boustead 1992]. The introduction of the ISO 14040 standard [ISO 14040 ff. 1997], which outlines the procedure and requirements of an LCA, may contribute to the reduction of misused LCA results.

COST is a prohibiting factor since many organisations are not prepared to spend a relatively large amount of man-hours on carrying out an LCA

LACK OF A COMMON CURRENCY inhibits a direct comparison of different environmental impacts an. On the other hand Benda *et al.* [1993] argues that the main purpose of an LCA is to represent and not compare. A reason against the common currency is that a single environmental indicator can not be recommended as "it represents the classical controversy of comparing apples and pears" [Alting & Brøbech Legarth 1995].

BOUNDARY CONDITIONS influence the results and need therefore be stated clearly. This is a common cause for differences in LCA's [Boustead 1992].

WEIGHTING FACTORS are often used in the interpretation phase for relating the relative importance of various emissions. These weighting factors can be debateable especially when they are not based on 'hard' scientific evidence.

DATA AGGREGATION requires that the amount of data is reduced, so that it is manageable for decision makers.

[17] Most of the problems stated here are also applicable to carrying out an GER analysis.

[18] For up-to-date LCA's it is obvious that up-to-date data is used which sometimes can be difficult to obtain.

The described problems described above show briefly what one has to consider when carrying out an LCA on a product. It is also important to take into account practical aspects when developing a LCA (or Life Cycle Design) methodology. One of the most important aspects of LCA is that it should be consistent across experimenters, products and locations [Benda *et al.* 1993].

2.5 Gross Energy Requirement (GER)

Many aspects discussed in this section also apply to life cycle assessment and were therefore no repeated in Section 2.4.

Energy is the key to making things happen and for any real process to take place energy has to be 'expended'. Primary energy is available in various forms and quantities, e.g. in the early 70's 97% of the primary energy for industrial processes came from fossil fuels, of which 38% were solid (coal, wood), 40% were liquid (oil) and 19% were gas fossil fuels [Lovins 1975]. The solid and liquid fossil fuel demand doubled about every 10 years while the gas fossil fuel demand doubled every 7 to 8 years. Other sources of energy, such as nuclear power are of more significant importance today and hydro, wind and solar power are becoming more and more important as these technologies become more efficient and economically viable, but they represent even today a low proportion of the overall primary energy when compared to fossil fuels.

The Gross Energy Requirement (GER) is used as one measure among others in LCA's. It describes the energy that has been used due to the making, usage and disposal of a product — or, in short, due to the existence of the product. Loosely speaking it can therefore be described as an 'energy content', but in a physical sense this is obviously wrong, as the product does not store the energy that was used to make it, except maybe a minute fraction. This notation serves to visualise that energy was used due to the existence and use of the product. It is useful as a part of a full LCA as it indirectly describes a considerable fraction of the environmental impact [Häuslein & Möller 1995]. To this effect Glatzel and Kaschenz [Glatzel & Kaschenz 1995] have said that

> ...GER can be compared to the technically superbly simple stethoscope in medicine; as with the stethoscope it is *not* the one and only diagnostic tool, but it can be used for a 'rough check' of the 'key organs', the heart and lung. Energy also is a *key* measure.

The GER of a product[19] or a service is the total energy expended over the entire life cycle due to the existence of the product or service. Usually the GER is differentiated in two ways [Häuslein & Möller 1995]:

1. according to the life cycle stages[20]
2. according to the primary energy carriers

The first method is useful for information on the life cycle stages while in the second method the primary energy carriers can be directly identified for each process.

The energy analysis of products is one of the least controversial phases in LCA as it requires little or no interpretation. The GER can be more or less directly read from the inventory phase of the LCA which describes the in- and outputs of a system. On the other hand there is a problem associated with getting the reliable and relevant[21] energy data from industry [Wagner 1996].

Important questions that need to be addressed in any analysis of the GER or indeed for any LCA are to what extent does the outcome of an analysis depend on the questions asked and on the aim of the analysis respectively[Glatzel & Kaschenz 1995]. Further, how does the GER depend on regional aspects? E.g. will the GER_{Use} be the same for an electric car whether it is driven in Norway or in Britain? Obviously the GER_{Use} in primary energy terms will be quite different as the Norwegian energy comes predominantly from hydro-power while in Britain it comes mostly from fossil fuel.

Analysing a product with respect to its GER can help to chose an energetically optimised product and an energetically optimised useful life of energy consuming and energy converting products [Schaefer 1993]. This is also shown in the calculation of a so-called amortisation time t_{amort} which is the time in the usage phase in which a product 'repays' the energy that was used before the usage phase, i.e. during the manufacturing and preceding phases. The repayment can be indirect in terms of energy saving or direct in terms of providing energy from renewable sources[22] and therefore substituting energy from non-renewable sources [Wagner 1996].

In [Glatzel & Kaschenz 1995] it is concluded that GER should be developed as an independent practical measure for resource efficiency and that it should be used

[19] If the GER of a product is mentioned then this means that the cumulated energy over the life of the product or material up to the stage mentioned is in terms of *primary energy* except where stated otherwise.

[20] Manufacture, usage and disposal or in more detail for each of the processes.

[21] E.g. the data should not be out of date.

[22] Sometimes it is argued that nuclear energy has the same benefit as using energy from renewable sources, which is only true from the CO_2 and other gaseous emissions point of view, but it is too expensive to be used for that reason alone and carries a further considerable risk along the whole fuel chain [McLaren, Bullock & Yousuf 1998].

as a 'stethoscope' for environmental protection, but it has to be made sure that complications based on an understandable desire for scientific detail are opposed. But it is also argued that the life cycle should be clearly defined and that the errors due to omission and approximation should be kept as small as possible [Wagner 1996].

2.5.1 The Method of Boustead & Hancock [1979]

The method of Boustead & Hancock [1979] describes a LCI model and is concerned with energy analysis of industrial processes, which was later extended to include untreated waste streams. Boustead looks also at the implications of e.g. recycling loops and makes suggestions how to solve these problems.

The forms of energy are distinguished in some detail, i.e.

- the fuel production energy, i.e. the energy that is required to make the fuel (and therefore energy) available at the point of use
- the actual energy content of the fuel at the point of use
- inherent feedstock energy of the product that can be released in, say, an incineration process.

In **Tab. 2.4** it can be seen how the method represents the energy requirements of a system and retaining the detailed breakdown by fuel types and fuel production energy, actual energy content and the inherent feedstock energy.

Table 2.4: Showing the method of representing the energy requirements but still retaining the detailed breakdown by fuel type [Boustead & Hancock 1979]

Fuel Type	Fuel Production Energy [MJ]	Energy Content of Fuels [MJ]	Feedstock Energy [MJ]	Total [MJ]
Electricity	A	E	K	R
Oil Fuels	B	F	N	S
Other Fuels	C	G	P	T
Totals [MJ]	D	H	Q	V

This method is applied in an extended form to The Boustead Model [2000], which presents inventory data on industrial systems to form whole networks. The data for the individual processes are represented in relative terms as unit processes with one product as an output. In addition the processes are linked through their respective constituents (materials, energy inputs, waste streams), thus taking into account the

interrelationship of the processes. This is a more realistic presentation since the global industry is not the sum of isolated individual systems, but all the systems interact and therefore influence a total efficiency of an industry. An example is that the electricity production energy is influenced by the steel making industry, so that e.g. an increase in efficiency in steel making will increase the electricity production efficiency.

This model incorporates a large detail of information on the inventories of industrial production systems, ranging from the mining industry, fuel production industry, engineering materials bulk processing industry, several production processes, to the power generating industries of major industrial countries.

2.5.2 The Method of Schaefer [1993][23]

This method looks at a way of describing the GER in as complete a way as possible. It follows generally accepted ways, such as that the boundary conditions can only be drawn once a rough quantitative analysis has been carried out on the excluded phases [Schaefer 1993, Boustead 1992] and that one should make certain that the energy expenditure of the various stages is only attributed once to the product. It is argued to use the measure of primary energy as this is the only realistic way to compare the various forms of energy. Furthermore this allows one to make a statement on the resource strain.

It is noted that material and energy flows should not only include those for the product in question but also those of coupled products, whether they are waste or sellable.

Schaefer [Schaefer 1993] describes a mathematical model where the GER is subdivided into

- Manufacture GER_{MP}
- Usage GER_{Use}
- Disposal GER_{Disp}

with the total being

$$GER_{total} = GER_{MP} + GER_{Use} + GER_{Disp} \tag{2.22}$$

Here the GER *of each phase* is the sum of the *process energy requirement* (PER) and the *cumulative non-energetically used energy content* (CNE) so that

$$GER_x = \sum_{i=1}^{m} PER_i + \sum_{i=1}^{n} CNE_i \tag{2.23}$$

[23] A method very similar to this is also adopted in the *VDI-Guideline 4600* (VDI-Richtlinie 4600) [Wagner 1996]

where x means MP, Use or $Disp$; m is the total number of processes required for x and n is the total number of non-energetic terms associated with x.

The CNE is the sum of all *non-energetically used fuels* (NUF) and of the *bound energy content* (BEC) that could be freed otherwise in an exothermic reaction. Therefore

$$CNE_i = NUF_i + BEC_i \tag{2.24}$$

Furthermore the PER includes electricity and fuel energy that is used due to the process, e.g. light, heating and machines, and which can be directly correlated to the process.

A coefficient of disposition, c, needs to be included for all energy terms. This coefficient is a link between the energy that is available at the point of use and the primary energy that was required to make it available.

$$c = \frac{\text{energy content of fuel at place of use}}{\text{cumulative primary energy expenditure for disposition}} \tag{2.25}$$

In the case of secondary energy, such as electricity, an average coefficient of disposition (here e_{el}) can be derived from the national or regional proportion of the electricity production.

$$c_{el} = \frac{E_{el}}{\frac{a_1}{c_{el_{fossil}}} E_{el_{fossil}} + \frac{a_2}{c_{el_{regenerative}}} E_{el_{regenerative}} + \frac{a_3}{c_{el_{nuclear}}} E_{el_{nuclear}}} \tag{2.26}$$

where a_1, a_2 and a_3 are proportionality factors representing the proportion of energy produced with each technology (i.e. fossil, regenerative and nuclear) within a country or region.

In this paper the difference between the methods of allocating the primary energy to renewable energy is discussed. One method looks at substituting the renewable energy conversion efficiency with that from those conversion efficiencies observed when using fossil fuels as the primary fuel (called *substitution method*) and the other method acknowledges that you can use the information available from the technology and use the *real* conversion factors. In case of hydro power the real conversion efficiency is about 85%, i.e. the ratio of the net-energy produced to the potential energy of the water. According to the substitution method you would allocate a conversion efficiency of only 38.6%. This can obviously lead to misleading results especially for countries with a high proportion of regenerative power generation.

Another feature of the method worth mentioning is the *technology factor* introduced to estimate the conversion efficiencies in other countries compared to a country where data is known in detail. This technology factor is used to take into account older and less efficient technology that is involved in the energy generation and simply scales the conversion efficiency according to that estimate. Obviously, this can be a very

subjective way if it is not founded on evidence that supports the allocation of the technology factor.

The example given in the report looks a virgin aluminium imported from various countries into the Federal Republic of Germany. Knowing the percentage of electric energy coming from fossil fuels, hydro power [24] and nuclear fuels an overall *net conversion efficiency* [25] is calculated. The net conversion coefficients of all the countries is averaged taking into account the percentage import from each country. This results in an *average net conversion coefficient* for a material as it is used in one specific country. This is then used to determine the primary energy associated with that material when used in that specific country.

2.5.3 Boundary Conditions for GER Analysis

As with LCA studies, the boundary conditions need to be defined in a clear manner to avoid misinterpretations. Furthermore the boundary conditions should describe the physical system in as complete a manner as possible to avoid overlooking vital information.

Boundary conditions can be chosen according to the following criteria [Wagner 1996]:

- local criteria, based on geographic location,
- temporal criteria, based on time of events and
- technological criteria, based on the technology used.

The completeness of a system requires the sensible choice of boundary conditions. The important question of to what extent the GER is influenced by the boundary conditions [Glatzel & Kaschenz 1995] can be analysed by varying the boundary conditions and to evaluate the influence of the boundary condition [Häuslein & Möller 1995].

In [Boustead & Hancock 1979] the boundary conditions are described by defining a *vertical* and *horizontal* structure of a system.

2.5.3.1 Vertical Completeness

The vertical structure of a system is the structure that describes the processes that are required for the actual process to take place. An example [Boustead & Hancock 1979] is that the

- first order process is to pump water, then the

[24] It is argued that other renewable sources of energy played no significant part and therefore they just look at hydro-electric power.

[25] The net conversion efficiency includes the coefficient of disposition and the technology factor.

- second order process is the pump manufacture, the
- third order process is the production of the machine that makes the pump
- and so on ...

According to [Boustead & Hancock 1979] for most systems a process chain can be truncated after the second order process as the higher order processes have a negligible influence on the overall system.

The vertical structure can be compared to the fixed overheads of pumping water, i.e. buying the pump, buying a machine to make pumps, etc.

2.5.3.2 Horizontal Completeness

The horizontal expansion of a system are the inputs that are required *directly* for a process to take place and are therefore proportional to the process' output. The horizontal structure can be compared to the variable (proportional) cost of an operation, such as material and labour cost. In the case of pumping water it would be the direct energy to run the pump.

For a system to be horizontally complete all the sub-systems have to be included until the inputs are derived from the earth and the outputs go eventually back into the earth or atmosphere.

2.5.4 The GER of Coupled Products (Allocation)

The main product is often accompanied by the production of some secondary products (coupled products) in a number of real production processes. Therefore it is important to partition the GER, as only a part of the GER can be associated with the main product. The problem of assigning a proportion of the GER to the coupled product is addressed in various ways [Boustead 1992, Häuslein & Möller 1995, Wagner 1996].

In [Boustead 1992] it is suggested that the GER of the coupled products can be partitioned by breaking the system down into subsystems where each subsystem produces a single product, but all subsystems together exhibit the same characteristics as the original single system. To do this it is necessary find a suitable partitioning criteria.

The criteria used for assigning the GER to the coupled products can be quite different from system to system and they need to be analysed carefully to evaluate the influence of the 'coupling factors' on the end result [Häuslein & Möller 1995]. The separation of the energy and raw material input can be achieved according to the following criteria [Wagner 1996]:

- Correlation of the total energy expenditure based on the principle of the product or products that caused it.
- Separation based on physical measures such as mass, volume or amount.
- Separation based on energetic measures such as calorific value or enthalpy.
- Separation based on economical values such as market price[26].

The case of closed recycled materials is seen as a special case according to [Häuslein & Möller 1995]. It is argued that closed loop recycled materials should be considered as 'energy free'[27] with respect to their GER as the GER of the primary product has taken into account the GER of the recycled material. This is a simple approximation due to linear representation of the process chain, which can lead to significant errors in the determination of GER [Boustead 1992]. A simple network representation for the recycling system can solve the problem [Boustead 1992].

In the author's opinion it is worth trying to treat recycled materials as coupled products where the main product 'produces' scrap material which is recycled at a later stage. In addition to the apportioned GER, the GER for transport, sorting, processing, etc. is added.

2.5.5 GER and Emissions

The cost of energy has reduced since the late seventies, so that the interest of reducing the energy consumption form an economic point of view has also reduced [Schaefer 1993]. But GER has direct links to emissions and from this point of view the GER should be minimised taking into account the emissions due to both energy and non-energy related processes. This will become even more important as the cost of emissions rises. According to [Schaefer 1993] GER can be used to estimate emissions. On the other hand, the question whether the minimisation of the GER of a product or service will automatically lead to a minimisation of the total energy related emissions is still in discussion [Glatzel & Kaschenz 1995].

2.5.5.1 Energy and CO_2

In [Saur & Finkbeiner 1997] it was pointed out that the usage phase of active and passive 'energy consuming' products dominates the total life cycle combustion emissions such as CO_2. Especially for large 'energy consuming' products such as a

[26] According to [Boustead 1992] this is an unsuitable parameter as the systems are physical systems which depend on the technology employed and not on market values which can vary significantly even thought the technology and practices remain the same.

[27] Except for the calorific energy.

power station, it was not surprising that in the case of fossil fuel fired power stations the usage phase is dominant for CO_2 emissions [Lewin 1993]. On the other hand for non-fossil fuel power stations, such as nuclear, photovoltaic and wind power stations, the dominant life cycle processes with respect to CO_2 emissions are the processes before and after usage [Lewin 1993]. This is obviously due to the nature of the non-fossil fuel required for the usage phase in the latter cases.

The relationship between various types of power stations[28] and the CO_2 emissions where analysed, including the energy chains of the pre- and post-processes of the power stations [Lewin 1993]. It also included Methane (CH_4) by defining a CO_2 equivalent; this is based Methane's properties as a greenhouse gas which are about 32-times[29] larger than that of CO_2 per molecule. The investigated scenarios (see **Tab. 2.5** for results) were that the energy used for processes preceding and following the actual energy conversion process where taken from

1. the national grid[30]
2. the type of power plant investigated
3. the national grid[30] and the use of the heat of the power plant for industrial and domestic purposes (where possible[31])

The outcome of the study is that the associated specific CO_2-emissions [in $\frac{gCO_2}{kWh_{el}}$] are increased significantly by the inclusion of the pre- and post-processes, especially in the first two cases. The results are displayed in **Tab. 2.5**.

Table 2.5: CO_2-emissions [in $\frac{gCO_2}{kWh_{el}}$] for electricity from various types of primary energy [adaped from [Lewin 1993]]

Case[a]	Power Station Type					
	Pit Coal	Brown Coal	Natural Gas	Photo-voltaic	Nuclear	Wind
1	1244	1206	453	228	28	11
2	1249	1245	452	72	5	8
3[b]	915	—	357	—	—	—

[a] scenarios listed above

[b] in $\frac{gCO_2}{kWh_{el}+kWh_{th}}$

[28] Pit coal fired, brown coal fired, natural gas fired, photovoltaic (PV), nuclear and wind power station

[29] Factor is uncertain due to the inconsistent breakdown times of CO_2 and CH_4 in the atmosphere of the various climate-models. Therefore the CO_2-equivalent of CH_4 is less for periods larger than 20 years and increased for periods of less than 20 years.

[30] This was based on the German mix of power plants.

[31] This was only possible for pit coal and gas fired power stations as they are usually located near populated areas and produce heat in sufficient quantity.

It can be seen that electric energy from both coal fired power stations incurs the largest specific CO_2-emissions, i.e. ca. $1200\frac{gCO_2}{kWh_{el}}$ for case 1 and 2. The gas fired power station incurs about $450\frac{gCO_2}{kWh_{el}}$ in case 1 and 2. The values for cases 1 and 2 are so similar for coal and gas fired power stations because these technologies represent the majority of the German electricity generation, so that the actual power plant data and the national grid average data differ little.

The photovoltaic (PV) power station generated $228\frac{gCO_2}{kWh_{el}}$ for case 1 which is mainly due to the energy intensive production of PV-cells and the relative low solar energy flux in northern Europe.

The specific CO_2-emissions of the nuclear and wind power station is in contrast to the other technologies relatively low.

The industrial or domestic usage of the otherwise lost process heat reduces the specific CO_2-emissions by about 20% to 25% to $915\frac{gCO_2}{kWh_{el}+kWh_{th}}$ in the case of the pit coal fired power station and to $357\frac{gCO_2}{kWh_{el}+kWh_{th}}$ for the gas fired power station. Obviously this scenario describes only a minority of power stations and is therefore applicable in very few cases. It has to be seen to what effect the national average is influenced by the wider use of this technology. It definitely shows the advantage that combined heat and power units have on the overall efficiency and therefore on CO_2-emissions.

The CO_2-emissions that are associated with the pre- and post processes are different for the different technologies. In the cases of the nuclear fuel and natural gas the CO_2-emissions of the pre- and post processes come mainly from the processing and transport of the fuel (energy related CO_2) while the pit coal emits Methane (giving rise to a process related CO_2 equivalent) and PV give rise to material related CO_2.

2.6 Costing

Designers need tools and methods to estimate the cost of their designs as early as possible during the design phase. As mentioned in Section 2.3.1 the unifying thoughts behind Design for Manufacture (DfM) and Design for Assembly (DfA) are to minimise the cost of the product before it leaves the factory by making products production and assembly 'friendly'.

These strategies do not include the whole life cycle and may lead to an increase of the total life cycle cost if, e.g. the DfA rules may result in a design that is not maintainable and therefore has to be discarded at the first sight of damage. Compromises between the various methods would be needed to achieve the best overall result.

The main costing methods mentioned here are those which have been specifically aimed at the early determination of cost in the concept stage of the design process. All methods have in common that they are usually quite inaccurate, but the earlier

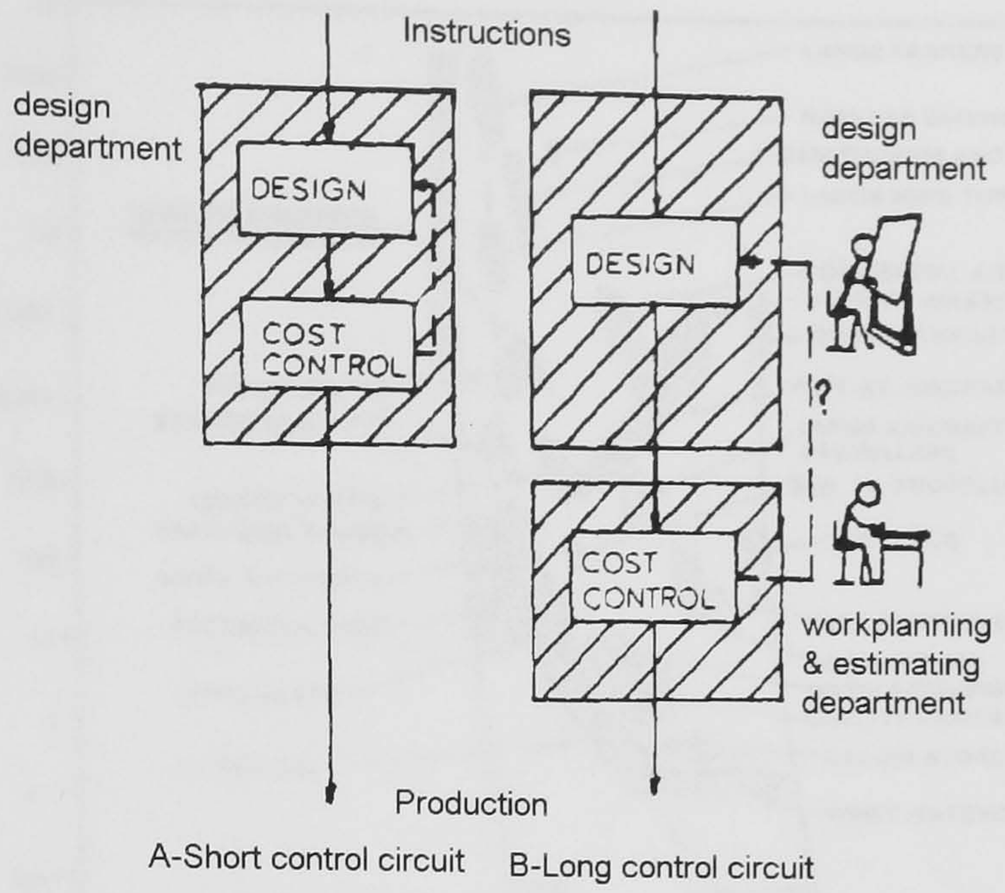


Figure 2.6: The control mechanism between synthesis (concept and embodiment of the design) and analysis of cost (work planning and costing) is inhibited and too sluggish if the two are separated (adapted from [Ehrlenspiel *et al.* 1979])

the cost estimation is carried out the more inaccurate it may be [Ehrlenspiel *et al.* 1979]. Therefore methods are required that have incorporated financial and technical information of the design so that the first cost estimations can take place during the early design process. This also reduces significantly the control loop of the cost analysis and design synthesis as is illustrated in **Fig. 2.6**.

In the following general techniques for minimising the cost of products are briefly explained.

2.6.1 Macro Scaling Using Weight

The macro scaling approach[32] is a method for estimating cost at the early stage of the design phase by utilising the empirical fact that for related assemblies the final cost is approximately proportional to the products weight [Esawi 1994, Meisl 1988]. An example is shown in **Fig. 2.7** where the weight of the unit [in lb] is correlated to the specific selling price of the unit [in $\frac{\$}{lb}$]. It can be seen that the weight based cost estimates are highly dependent on the complexity of the product.

The so-called "nonaircraft mediant" in **Fig. 2.7** reflects a trend that the higher the weight of a product then, in general, the lower the specific selling price.

A draw back of this method is that it is relatively crude as a cost estimation cost and e.g. it cannot help a designer when making design decisions on materials, as the change

[32] Also called top-down cost evaluation [Meisl 1988].

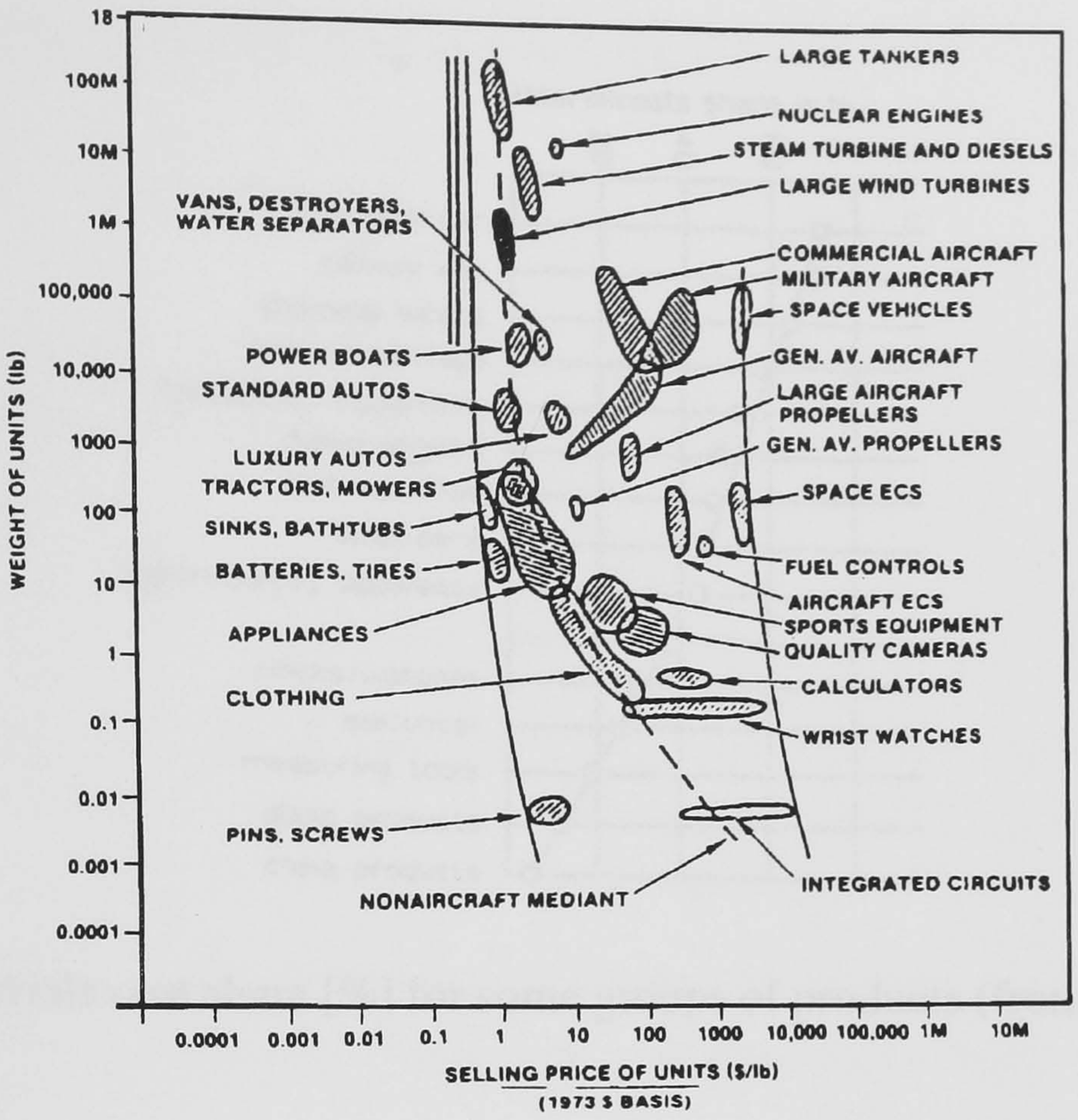


Figure 2.7: Weight-based unit production price (from [Meisl 1988])

of materials does not necessarily entail a significant change in weight but it could influence the product cost significantly.

2.6.2 Macro Scaling Using Material Cost

A slightly different correlation is used to estimate the final product cost by relating it to the material cost. Two methods are explained in the following.

2.6.2.1 The Method according to VDI 2225 [VDI-Richtlinie 2225 1977]

This method requires that if the product is similar in construction then it is assumed that the ratio of the material cost to the final product cost, $R_{EM/P}$, is equal for all similar products. The average ratio $R_{EM/P}$ is determined for many different market sectors. But they should rather be used as control values for comparison with company values [Beitz & Klasmeier 1982]. In **Fig. 2.8** an example of the material costs as a percentage share form the total cost is given for a selected group of products.

The absolute material cost can usually be determined quite early in the design process and by dividing the total material cost, $\sum_i C_{(EM)i}$, by the ratio $R_{EM/P}$ the total product, C_P, cost is easily determined, i.e.

$$C_P = \frac{\sum_i C_{(EM)i}}{R_{EM/P}} \tag{2.27}$$

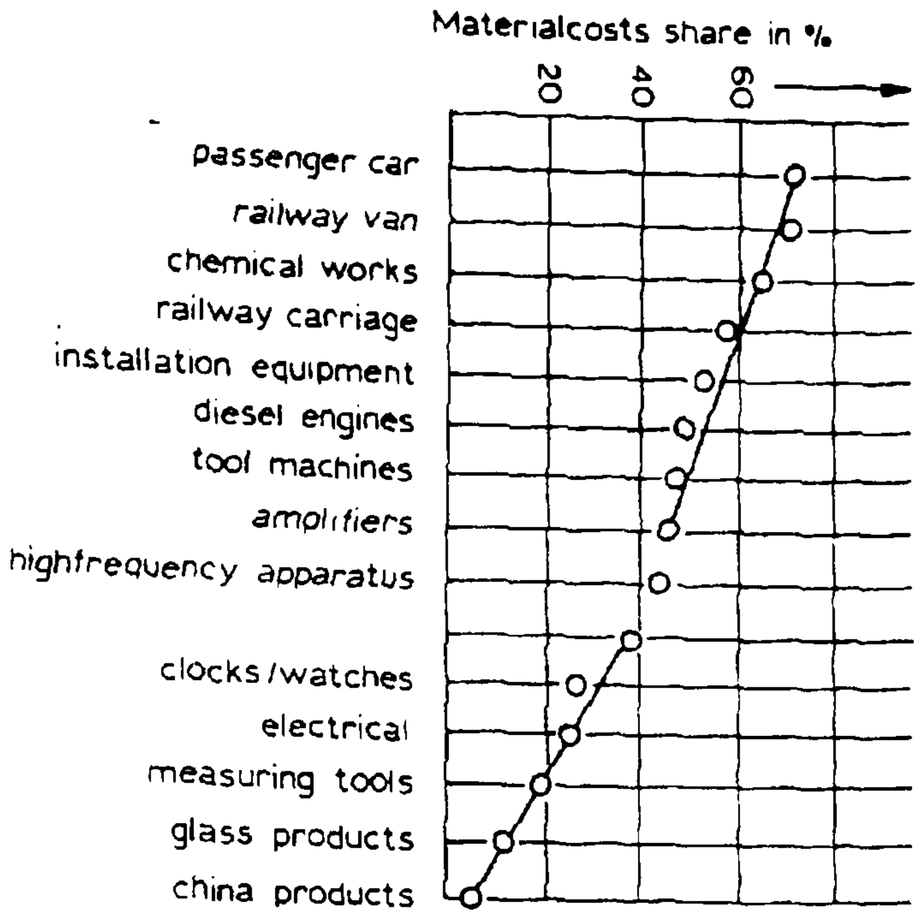


Figure 2.8: Materials cost share [%] for some groups of products (from [Hubka 1982])

This method is slightly more sophisticated than macro scaling with product weight and not taking into account the material cost as it was explained in the previous section. It is stressed that it should only be used where the product is made of a large number of parts [VDI-Richtlinie 2225 1977].

2.6.2.2 The Method of Esawi [Esawi 1994]

The method explained previously is also a rough approximation of the final cost, but in [Esawi 1994] the method was further developed so that the method could be used to optimise the production process in relation to material, capital and labour cost. Here a cost ratio $R_{P/EM}$ is introduced:

$$R_{P/EM} = \frac{\text{Specific Product Cost}}{\text{Specific Material Cost}} = \frac{c_P}{c_{EM}} \tag{2.28}$$

A cost ratio of $R_{P/EM} > 10$ (i.e. material cost is less than 10%) is characteristic for sophisticated products which are produced in small numbers. A cost ratio of $R_{P/EM} < 10$ (i.e. material cost is more than 10%) is characteristic for mass produced products [Esawi 1994].

The specific cost of a product, c_P, is said to consist of material cost, a contribution due to the capital cost and direct and indirect labour cost.

$$c_P = \frac{c_{EM}}{1-f} + \frac{C_{Cap}}{m\,n} + \frac{\dot{C}_{Lab}}{m\,\dot{n}} \tag{2.29}$$

where f is the material efficiency of the production process, m is the product mass, n is the total number of products produced, $\dot{n}$ is the production rate

Dividing **Eq. (2.29)** by c_{EM} gives an expression for $R_{P/EM}$:

$$R_{P/EM} = \frac{1}{1-f} + \frac{C_{Cap}}{c_{EM} m\, n} + \frac{\dot{C}_{Lab}}{c_{EM} m\, \dot{n}} \tag{2.30}$$

The number of variables for the cost ratio $R_{P/EM}$ is reduced by assuming that capital cost and labour cost are linked in the following manner:

$$\frac{c_{Lab}}{c^0_{Lab}} = \left[\frac{C^0_{Cap}}{C_{Cap}}\right]^k \tag{2.31}$$

where $c_{Lab} = \frac{\dot{C}_{Lab}}{m\, \dot{n}}$. The current capital cost C^0_{Cap} and the current specific labour cost c^0_{Lab} are seen as constants so that an increase in capital cost[33] C_{Cap} will decrease the specific labour cost c_{Lab}. Also, $k > 0$ and usually $k > 0.5$.

Finally **Eq. (2.31)** is substituted into **Eq. (2.30)** and the cost ratio $R_{P/EM}$ is minimised by solving $\frac{dR_{P/EM}}{d\left(\frac{C_{Cap}}{C^0_{Cap}}\right)} = 0$ and substituting the result into **Eq. (2.30)**.

2.6.3 Costing Based on Similarity Correlations

The costing methods explained in this section exploit the similarity of designs and correlate the change in dimensions, while remaining similar, to the change in product cost.

2.6.3.1 The Method of Ehrlenspiel [Ehrlenspiel *et al.* 1979]

This method explained in [Ehrlenspiel *et al.* 1979] shows that there are similarity correlations which are generally valid independent of time and location. This is especially valid for the correlation of cost and constructive parameters, such as batch size, size of part, wall thickness[34], etc. The final cost, C_P, of the product is determined as a function of the ratio of the size for which the costs are known to the new size, i.e. a scaling parameter R so that $C_P = f(R_{d_i/d_j})$, where e.g.

$$R_{d_i/d_j} = \frac{\text{Diameter of known shaft}}{\text{Diameter of new shaft}} \tag{2.32}$$

where j refers to the new size and i to the known size. The sizing variable is R_{d_i/d_j} and the influencing constants are the fixed costs C_{Fix}, the batch size n, the ratio of the manufacturing cost to the total cost R_{C_{Prod}/C_P} and the ratio of the material cost to the total cost R_{C_{EM}/C_P}. From theoretical and empirical analysis the relationship of R_{d_i/d_j}

[33] E.g. investing into a less labour intensive production process without reducing the production rate or even increasing the production rate.

[34] Especially important for injection moulded parts.

and the constants are determined and in the example given in [Ehrlenspiel *et al.* 1979] it takes the following form:

$$(C_{(P)j})_n = (C_{(P)i})_n \times \left[\frac{C_{(Fix)i1} R_{d_i/d_j}^{0.5}}{n} + R_{C_{Prod}/C_P} R_{d_i/d_j}^2 + R_{C_{EM}/C_P} R_{d_i/d_j}^3 \right] \tag{2.33}$$

where n to the batch size. In this case the function is valid for

- same construction, but just scaled in size
- no change of the manufacturing method (in this case cutting methods)
- no dependance of the material price on the batch size

It can be seen that the method is useful when scaling designs, but the designer still needs to have a reference object against which the new object can be scaled.

2.6.3.2 The Method of Pahl and Beelich [Pahl & Beelich 1979]

A different method was introduced in [Pahl & Beelich 1979, Pahl & Rieg 1982, Pahl & Beelich 1982] where the similarities of the price are determined using so-called 'growth equations', or in [Wierda 1988] they are called 'cost increasing functions'. These are used to determine the difference of a known design to the cost of a new design.

It is said that the total production cost C_{Prod} is made up of the sum material cost C_{EM}, labour cost C_{Lab} and overhead costs C_{OH} so that

$$C_{Prod} = C_{EM} + C_{Lab} + C_{OH} \tag{2.34}$$

The overhead costs are allocated to the material and labour cost by defining an allocation factor $k_{EM} = \frac{\sum \text{Overhead Costs}}{\sum \text{Material Cost}}$ and $k_{Lab} = \frac{\sum \text{Overhead Costs}}{\sum \text{Labour Cost}}$ so that

$$C_{Prod} = C_{EM} + (1 + k_{Lab}) C_{Lab} \tag{2.35}$$

when considering the material cost first, then it can be said that

$$C_{EM} = (1 + k_{EM}) c_{EM} V_{EM} \tag{2.36}$$

where c_{EM} is the price per volume of the material and V_{EM} is the volume of the material.

E.g. example the material could be pipe; then

$$V_{EM} = A \times L \tag{2.37}$$

$$A = \frac{\pi}{4}(D^2 - d^2) \quad \text{so that} \tag{2.38}$$

$$C_{EM} = (1 + k_{EM}) c_{EM} \frac{\pi}{4}(D^2 - d^2) L \quad \text{or} \tag{2.39}$$

$$C_{EM} = (1 + k_{EM}) c_{EM} \frac{\pi}{4} \left(1 - \frac{d^2}{D^2}\right) D^2 L \tag{2.40}$$

where A is the area, L the length, D is the outer and d is the inner diameter of the pipe. Assuming that $(1 + k_{EM})$ and $\left(1 - \frac{d^2}{D^2}\right)$ are constant which is the case in most of similar parts, then with

$$\alpha_{EM} = (1 + k_{EM})\frac{\pi}{4}\left(1 - \frac{d^2}{D^2}\right) \tag{2.41}$$

$$C_{EM} = \alpha_{EM} c_{EM} D^2 L \tag{2.42}$$

Therefore the material cost for the original design will be

$$C_{(EM)0} = \alpha_{EM} c_{(EM)0} D_0^2 L_0 \tag{2.43}$$

and for the following design it will be

$$C_{(EM)1} = \alpha_{EM} c_{(EM)1} D_1^2 L_1 \tag{2.44}$$

Therefore the ratio of the two can be expressed as

$$\frac{C_{(EM)1}}{C_{(EM)0}} = \frac{\alpha_{EM}}{\alpha_{EM}} \frac{c_{(EM)1}}{c_{(EM)0}} \frac{D_1^2}{D_0^2} \frac{L_1}{L_0} \tag{2.45}$$

which in another form is termed the aforementioned 'growth equation' for, in this case, engineering materials, δ_{EM}

$$\delta_{EM} = \delta_{c_{EM}} \times \delta_D^2 \times \delta_L \tag{2.46}$$

If this equation is determined then the designer can calculate the material cost of future designs from knowing the cost of the original design.

Similarly the 'growth equations' can be determined for the production cost of the different manufacturing methods.

Furthermore the method was extended to be valid for semi-similar objects, i.e. when one dimension does not scale up to the same degree as the other dimension.

2.6.4 Life Costing of a Design

Most of the methods described previously do not take into account the phases that follow the production of the product and therefore are of limited value when considering the whole life cycle cost of products. In this section the concept of life costing is introduced.

Life costing is a method where the whole life of a product is taken into account when determining the real cost. This therefore includes in addition to the pre-usage phase the usage phase and the disposal phase of the product.

Evaluation methods of designs where monetary terms are used as the evaluation criteria is a practical way of demonstrating the benefit of one decision over another. This can

be compared to the EIA methods in LCA where the 'weighting' is not carried out as show in Section 2.4.5, but instead of weighting factors the life costing methods use conversion factors to arrive at monetary terms as the common unit[35]. Environmental considerations are usually not included in life cycle costing methods as money is inappropriate for evaluating environmental impacts.

The life cycle costing method introduced in [Fu & Cebon 1997] takes into account the life cycle phases (except disposal) by including the following:

- routine maintenance,
- fuel consumption,
- statistically expected cost of component replacement and repair (from simulation) due to abnormal failure,
- capital cost
- monetary benefit of product, i.e. how much does it earn

The paper concludes to be an objective method for comparing engineering designs that can even be used early on in the design process as long as factor can be estimated for converting performance attributes into life-time cost. This method has its benefit which were clearly demonstrated with the help of an example, but it requires quite detailed information on especially the statistical expected cost due to abnormal failure[36].

2.6.5 Other Costing Methods

A list of some other costing methods are listed below.

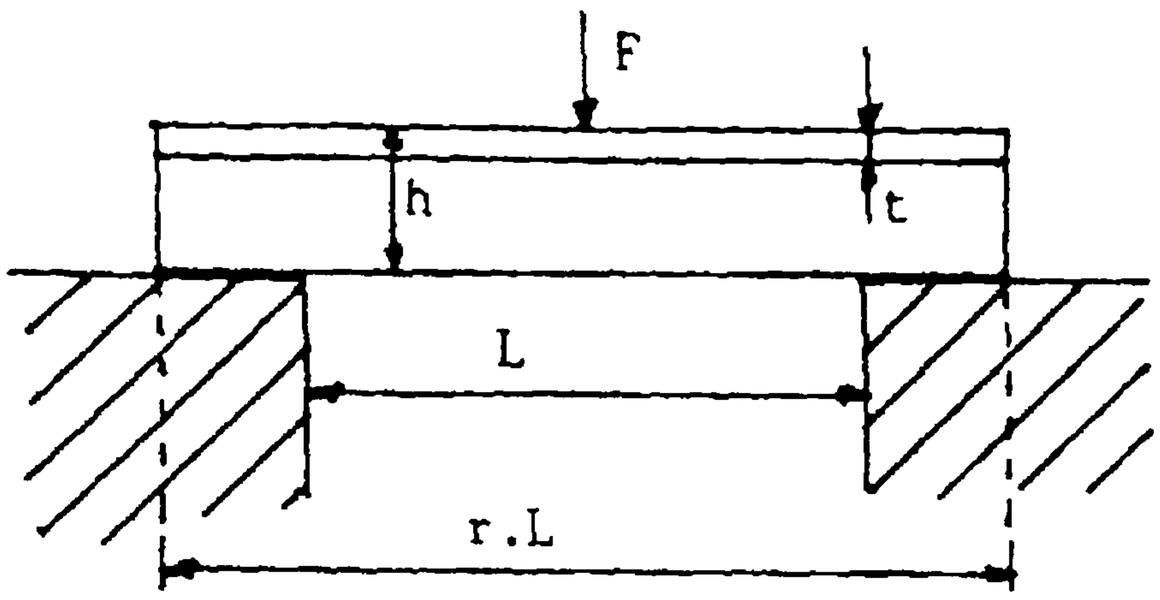
MACRO SCALING USING OUTPUT PARAMETERS In this method characteristic output parameters — e.g. energy output, compression, heating surface, filtering area — are related to the cost of the system. The scaling of these parameters allows a designer to determine the cost of different configurations [Kölbel & Schulze 1960].

This method is useful when comparing technical solutions with respect to their characteristic output parameters. This relative cost will vary between different physical principles and different technical solutions.

[35]The difference between the monetary terms and the normalised and weighed results of the LCA is that money is widely used throughout to 'weigh' objects and services. But many people using this measure does not mean that it is a more realistic and objective representation than any other developed measure.

[36]The cost due to abnormal failure was also the largest single cost overriding everything in the given example, so that a small error in the supplied information would have a pronounced effect on the outcome of the result.

DIMENSIONING METHOD This method combines[37] technical and economical variables into one equation yielding the costs as a function of product properties [Claussen, Oschanitzky & Selbmann 1982]. An example is given in **Fig. 2.9**.



Technical equation: $F.L = z_1.W.S_{bmax}$

Costs equation : $TC = A.r.L.Kv + b.r.L.Kf$

Dimensioning equation: $TC = F.L^2.\frac{r}{z_1}.\frac{6}{h}.\frac{Kv}{S_{bmax}}.(1+\frac{t.Kf}{h.Kv})$

Figure 2.9: Example of dimensioning equation which combines technical and economical parameters (from [VDI-Richtlinie 2225 1977, Wierda 1988]). Notation: h =beam height; b = beam width; $A = h \times b$, beam sectional area ; t = wall thickness; L = loaded length; $r \times L$ = beam length; Kv = material cost ; Kf = processing costs per unit area; TC = total cost; z_1 = clamp factor ; W = moment of resistance to bending ($b \times h^2/6$ for a rectangular beam) ; F = central load; S_{bmax} = maximum allowable bending stress.

Further examples given in [Claussen *et al.* 1982] show that the method can quickly tend to be rather complicated and so loosing clarity between the product parameters and the costs.

FUNCTION COSTING All products and services perform a function. Functions of a product or component include e.g. containing a liquid under pressure or converting energy while the functions of a service include e.g. the acquisition and distribution of data. Market forces tend to reduce the cost of performing a unit function over time, regardless how the function is performed. Historical data can be used to estimate the cost of each sub-system (performing one function) and this can then be added together to yield the total cost [Esawi 1994].

ACTIVITY BASED COSTING (ABC) is a product costing method where the costs are allocated to the individual activities rather than to traditional accounting entities.

[37]Called 'Bemessungslehre' in German

As is pointed out by [Cokins 1997], ABC is a translator of the general chart of accounts view, but it is not intended as a replacement of general accounting. The strength of ABC is to determine money loosing activities from money making ones.

In [Emblemsvåg & Bras 1997] a method was introduced that showed how monetary, energy and waste values could be considered in parallel and by the same methodology. The methodology is based on ABC and it is adapted to include energy and waste considerations. Furthermore the method uses fuzzy numbers to include the uncertainties of data and a Monte Carlo simulation technique is used to perform a sensitivity analysis.

RELATIVE COST is concerned how much a feature influences the design's cost. This can be a useful tool as the designer is often not necessarily interested in absolute cost, but requires to know which design is the cheapest one. Therefore relative cost information on, say, diameter and batch size is derived and represented so that the designer can see what changes cost relative to a reference product. It is argued that this form of cost information is not as useful as absolute cost information as it overs greater flexibility [Wierda 1988].

CLASSIFICATION OF PRODUCTS uses characteristic features of products which can be used to compare existing products in a class with a new product form the same class. Very often the information on products is displayed in a multi-dimensional space, which is able to fit all the products of that class [Wierda 1988].

TIMES AND RATES can be used to calculate quite accurately the cost of a product by calculating the time that is needed to process a part and multiplying this by the hourly rates for man and machine. This give the total processing cost. The obvious drawback of this method is that the designer needs to accurately predict the times required for all the processing operations and therefore this method is not ideal for early cost estimation but is useful for cost estimation in the later stages of product and process design [Wierda 1988].

INTELLIGENT COST CALCULATION PROGRAMMES are programmes that can use technical drawings information to make suggestions on how to save money and what the total cost is. These are developed to be integrated into or linked to a CAD programme so that the information can be used without needing to reenter it. These programmes are limited in their application, but they can cope with some specialist problems [Wierda 1988].

2.7 Previous Approaches to Life Cycle Assessment in Engineering Design

In this section practical methods for integrating LCA into the engineering design process are discussed. The common approach is to carry out a base line assessment of an existing reference product which is used as guide for the requirements for the next generation of products. During conceptual design rough/generic LCAs are carried out, increasing with detail as the design progresses to the embodiment and detailing phase. Rough and generic LCAs require the estimation of various material and emission quantities, which rely on the reference product (provided the design has not changed significantly) and the expertise to estimate of the analyst.

In Section 1.2 and Section 2.2 the relative importance of the concept stage on the overall design process in terms of committing life cycle cost and life cycle environmental impacts was illustrated. Product cost estimation methods have been developed to estimate especially the manufacturing and material cost at the concept stage (e.g. [Esawi 1994, Meisl 1988]) but there are no *dedicated* life cycle cost estimation and life cycle inventory estimation methods specifically aimed at the concept stage of the design process. Consequentially there is a need for LCA methods (and life cycle costing methods), that alow the *efficient* evaluation of design concepts. Such LCA methods should consider the characteristic lack of detail associated with the concept phase of the design process, while aiding the estimation of the LCI.

The aims of previous approaches can be generally split into two groups, which are to

- enable easy to use life cycle assessment, so called streamlined life cycle assessment tools (SLCA) which may be used for concept evaluation and
- integrate life cycle assessment into the design process

2.7.1 Streamlining LCA approaches

The main motivation for streamlining LCA is to accommodate the difficulties associated with conducting full LCAs. The difficulties mainly arise in the areas of accessing relevant inventory data, for the various life cycle phases of the product. The methods used by LCA practitioners for streamlining the LCA process can be divided into several groups [Weitz, Sharma, Peters & Baskir 1996]. They include the following quantitative approaches:

ELIMINATING LIFE CYCLE STAGES Upstream and/or downstream stages of the life cycle are removed.

ELIMINATING SPECIFIC INVENTORY PARAMETERS Depending on the impact category that is of interest, certain inventory parameters are included, while disregarding other inventory parameters. E.g. if the impact of concern is global warming, then greenhouse gasses are investigated.

LIMITING OR ELIMINATING IMPACT ASSESSMENT Impact assessment is often not addressed and the objective becomes a minimization of the emissions as opposed to the minimization of the impact ('less is better' interpretation).

USING SURROGATE DATA When data on a particular material or process cannot be found, then the data of a similar material/process is used.

LIMITING CONSTITUENTS TO A THRESHOLD QUANTITY Thresholds are used in full LCAs. If a constituent is below a certain threshold it is not included in the LCI. In full LCAs this threshold is often 1% (rule of thumb) of the life cycle total and in streamlined approaches this can be increased to 5% or 10%.

FOCUSING ON SPECIFIC ENVIRONMENTAL IMPACTS OR ISSUES The scope of a LCA is to focus on a specific environmental impacts or issues, determined by expert groups or the sponsor. Often the focus is on those impacts for which data is available, or on issues important to the organisation.

Qualitative approaches:

USING QUALITATIVE DATA In cases where quantitative data is not available, a qualitative evaluation relies on expert judgement to determine the importance of various environmental concerns for each product or process.

ESTABLISHING "SHOWSTOPPER" OR "KNOCKOUT" CRITERIA Focuses on specific issues where the criteria leads to an immediate decision. E.g. the issue can be "is any ozone depleting substance released during the life cycle?" If the answer is positive, then the solution is disregarded.

Each of these approaches risk the exclusion of significant impacts, but as industry can only utilise practical methods, LCA practitioners use one or a combination of the above to obtain a result with the resources available. The results obtained using SLCA approaches have to take into account the limitations.

In a strict sense, even the 'most complete' LCA is a streamlined LCA, since most (if not all) detailed LCAs of complex products rely on 'regional[38] and temporal[39] surrogate

[38] Inventory data on a material from one region is used while the material of the real product may come from an unspecified combination of regions

[39] The LCA is carried out for a product for a certain year, but often historical data for raw material and process inventories has to be used.

data' for raw materials and processes and constituents are limited to a threshold quantity (rule of thumb: 1% by volume or mass, see above list).

An example of a quantitative SLCA approach is presented in [Graedel 1998, Graedel, Allenby & Comrie 1995]. The approach is based on presenting data of key environmental information in the form of a matrix, which takes the form of target plots (a centre with five concentric circles and 25 spokes). The rings present the scale of the environmental score, with the outer ring representing the highest environmental impact (a score of 4) and the inner ring representing the smallest or no impact (a score of 0). Groups of spokes represent five environmental issues, material choice, energy use, solid waste streams, liquid waste streams and gaseous waste streams. Each group is subdivided into five life cycle stages, pre-manufacture, product manufacture, product delivery, product use and recycling/disposal.

The target plot visualises the results from the 5 by 25 matrix; it allows the user to see 'movement' along the spokes. The desired goal is to select alternatives with movement towards the centre of the target plot. The visual assistance of the approach makes it easy to interpret the results. Assembling the plots is not so simple, but detailed guidance is given to help users to establish values for the individual plots.

2.7.2 Integrating LCA into the Design Process

'Integrating' LCA into the design process is often seen as simply carrying out LCA in parallel to the design process. The material requirements are extracted from the design manually and entered into a LCA programme together with data on the companies manufacturing processes and information on the use and post-use phases.

This becomes more difficult with increasing complexity of the product and the earlier in the design process the LCA is carried out. For an LCA at the concept stage, the analyst has to estimate the material requirements, as the product is not defined in sufficient detail as to allow a detailed determination of the material requirements. The estimation is more difficult for complex products and often relies on a reference product.

For LCAs at the later stage of the design process, methods for *greater* integration[40] have been proposed, though non have been implemented in commercial software. They have in common that only the pre-manufacturing and manufacturing phase is assessed, while other phases are neglected.

[40] Avoiding data redundancy, by reducing the amount of LCI-relevant information that is repeatedly determined and input.

One trend is the automated extraction of material requirements from CAD-drawings, which can be used as an input to LCA programmes. The information does not include manufacturing data, which have to be entered manually.

A step further is the utilisation of a feature technology based CAD approach. Here the geometrical representation of the product is obtained by defining simple geometric objects through a predefined structure, which includes design features (e.g. geometry, dimensions) as well as manufacturing features (e.g. material, machining process). The objects are set in relation to each other to form a part, and the parts are arranged to define a product. Thus the product model includes structured inventory and inventory related information, that can be automatically extracted to determine an overall manufacturing and pre-manufacturing inventory.

An example is an assessment software which is a feature based CAD-programme and includes information on possible manufacturing methods, production costs and eco-toxicological data. It is primarily aimed at optimising the manufacturing method of the embodiment design, so that the emissions and costs due to manufacturing are minimised. The programme extracts geometric and feature information from the geometric feature model and so evaluate manufacturing costs and energy requirements during the manufacturing stage [Müller & Oestermann 1997*a*, Müller & Oestermann 1997*b*]. The disadvantage of this implementation is that it is a 'closed system', thus there is no possibility of interfacing the programme to exchange the product's pre-use inventory data with existing LCA software, which would allow a full life cycle assessment.

Other proposed methods considering the whole life cycle include the work by the Birkhofer group (e.g. [Schott, Birkhofer & Grüner 1997, Schott, Grüner, Büttner, Dannheim & Birkhofer 1997]), which aims at integrating process and product development by integrating, what they call 'environmental knowledge', into the design process. The main feature of the computer-based system is the interface to product and process development (CAD) and to internal and external environmental information. The environmental information is previous LCA data of materials, machine elements, sub-assemblies, etc. The method is aimed at the embodiment stage of the design process and does not include a systematic approach to include the use-phase of the product.

Several other methods are aimed at carrying out assessments of partial aspects of the life cycle; they represent specialist solutions and cannot be viewed as whole life cycle assessment approaches.

2.8 Further Considerations

2.8.1 Representing Variability of Data

One way of incorporating the uncertainty of data is to set bands for each value (fuzzy numbers) and to use a Monte Carlo simulation method to determine the statistical distribution of the end-result [Emblemsvåg & Bras 1997].

In the case where more data is available the fuzzy numbers could be replaced by actual statistical distributions, so that each mean value is accompanied by a standard deviation which represents the spread of the data.

2.8.2 Confidence of Data

Data that is used for LCA comes from various sources with different reliability. Reliability in this context is how reliable is a source and what ways do you have to verify data, in other words how confident can one be in accepting the correctness of the data.

One qualitative way of expressing how confident one can be with respect to the correctness of the data is to express the confidence by means of a *confidence value* [Benda *et al.* 1993]. The confidence value depends on the physical properties of the product, the technologies normally used and other practical considerations (e.g. from -3 to +3; where positive values indicate a high level of confidence in the data and negative values or 0 mean a low level of confidence)

The confidence values can be used as a classification whether or not to rule out data. In the case where the data is hierarchically structured this means that if a higher level node is rejected due to low confidence then the confidence of the lower level nodes (daughter nodes) do not need to be established.

2.9 Summary

This chapter has shown the different considerations that a designer has to take into account when designing products and services. In addition to the usual fulfilment of the functional requirements, the life cycle approach adds another parameter to the design that needs to be taken into account, if not even optimised. Therefore, the consideration of the whole life cycle does not make the design process any easier but it introduces another degree of complexity. Doing this is worthwhile from the point of view that it may show weaknesses and strengths of a design which otherwise would be overlooked. Decreasing the complexity of accessing relevant information will make life cycle analysis even more worthwhile.

The review of the design process in Section 2.2 has highlighted that the analysis of the design at *any* stage is of utmost importance. The decisions made at the concept stage are vital as they are expensive if they require changes at later stages of the design process, thus highlighting the need for an LCA method that can be applied at the concept stage. The major problem associated with LCA during concept design is the lack of definition of the design. This has to be taken into account into any LCA method which is aimed at the concept stage. In general it can be concluded, that only if LCA (at any design stage) incurs a relative low additional cost[41] to the overall design, will LCA become common during engineering design and 'life cycle design' be made a competitive.

In Section 2.3 the main design objectives, that a design is required to fulfil, have been summarised. It was shown that various design methodologies (DfX approaches) focus on the different life cycle stages and that LCD is an attempt to consider the whole life cycle during the complete design process. Process sequencing is a detailed method that can be only applied in the later stages of design, while process selection may be considered even in the early stages of the design process.

Life cycle analysis and various related aspects were described in Section 2.4. Carrying out a LCA means to analyses a product or service considering its whole life cycle. A complete LCA was shown to go through different phases of which the inventory analysis (LCI) (Section 2.4.4) and environmental assessment (Section 2.4.5) were looked at in more detail. The LCI methods where distinguished as micro and macro methods. The interpretation and EIA is included to show how the inventory is linked to real world problems and therefore shows what information should be included in the inventory to be able to carry out an EIA.

It was further shown that LCA is not a complex task when considering all the sub-tasks individually, but it grows to a complex task once the analyst tries to gather data and assemble a full LCA, i.e. for the *whole* life cycle and for a multitude of parts.

Methods for determining the cumulative energy content (GER) were described in Section 2.5. An important aspect of the LCI is the description of the in- and outflows of energy to and from a system. Furthermore GER investigations have already been carried out since the late 60's and therefore much expertise has been accumulated which is also relevant to LCA's. The boundary conditions (Section 2.5.3) and the treatment of coupled products (Section 2.5.4) is of particular interest to this study. The interrelationship of energy and CO_2-emissions (Section 2.5.5.1) may be used for crosschecking purposes.

[41] This cost may be recouped by the overall improvements of the design, which were suggested by the LCA results. But it cannot be promised before the LCA is carried out.

In Section 2.6 various costing methods have been summarised. Costing methods are being 'exploited' here as they represent a wealth of ways to link 'real world parameters' (e.g. mass) to the costing unit 'currency'. Straight forward ways to 'model' costing are the scaling methods described in Sections 2.6.1 and 2.6.2. These methods may be simple, but from the perspective of practicality they cannot be beaten, when it is required to gain a result of sufficient accuracy during the early stages of design. This is why they are widely used in industry for preliminary cost estimation. It will be shown in the remainder of this thesis that the scaling method using product mass and material mass can be utilised for analysing the life cycle at the early stages of design. The costing based on similarity correlations (Section 2.6.3) requires more detailed information than the scaling methods, but this method may offer some aspects for the purpose of life cycle assessment. The life cycle costing method (Section 2.6.4) is usually not used early on during design as the data required maybe known only at later stages of the design process. Furthermore, other costing methods are shortly described to complete a picture on the various available methods.

In Section 2.7 methods for assessing the life cycle in engineering design have been discussed. The methods were distinguished as 'streamlining approaches' and proposals for integrating the LCA into the design process. The first group focuses mainly on the reduction of data, by omitting life cycle phases, specific inventories or impact assessment. This approach risks the exclusion of significant impacts. The second group aims at integrating LCA into product and process development process, by developing computer-based systems. They have in common that they are aimed at embodiment design, when the detail is increased. The main conclusion from this review is that there exist no quantitative methods for life cycle assessment aimed specifically at and may be integrated[42] into the early stage of the design process.

Section 2.8 summarises relevant information on representing variability and confidence of data.

In the next chapter a method is introduced that focuses on the determination of an approximate LCI at the early stages of design.

[42] E.g. by avoiding data redundancy.

3 Modelling the Life Cycle Inventory

In the previous chapter the lack of and need for a quantitative assessment of the life cycle at the early stage of the design process was illustrated and the problems associated with this task were highlighted. In the following a method is described, addressing aforementioned problems (such as lack of detail, integration into the design process by avoiding data redundancy) and to enable quantitative life cycle assessment in engineering design, specifically during the early design phase.

3.1 Overview

Analysing different concepts, first requires the proposal of a concept. Decisions on the components (standard parts (e.g. machine elements), standard subassemblies, standard engineering assemblies) that make up the design concept will have been taken. The large majority of components in engineering design are standardised, mass produced and available from a large range (product family). In simple terms, parts, subassemblies and assemblies are arranged to form a 'bare product'. The 'bare product' is located within a housing, presenting a product. In this context it is reasonable to assume that the sum of a product's components' inventories yields the inventory of the product.

By determining the inventory of all the engineering standard components, it would be 'simple' to select the specific components of a product and add-up the inventories to determine the product inventory. But this is a near impossible task, as the number of available components is immense. In this thesis it is resolved by modelling the inventory of products over whole product ranges from various manufacturers.

The method is aimed at helping to answer LCA related questions in the early design phases. Questions may be of the nature:

> "What are the strengths of concept *'A'* compared to concept *'B'* with respect to the overall impacts?"
>
> and

"Which life cycle phase of my product is the dominant source of which impacts?"

and

"Which design parameters have the largest effect on the overall impact and therefore deserve particular attention for improvement?"

In answering such questions early during the design phase the designer can focus on the 'weak points' of the design from an early point, thus avoiding changes at a later stage during the design process.

When considering the intended use of the method described in this thesis, it is helpful to consider the relative importance of components within a product. E.g. in Chapter 5 the product is a hybrid electric vehicle. The components assessed are the electric motor and the lead acid battery. They were chosen as they bear a relative high importance on the whole product[1], while, say, parts of the electric motor, such as the bearings, bear little importance on the overall life cycle of the hybrid vehicle, assuming they are not the cause of a failure. As a consequence only the most relevant components are required to model a product sufficiently. Selecting the most relevant components can be based on a preliminary mass and energy evaluation; in other words "what are the largest components in my product and which components are likely to waste energy directly or indirectly during usage".

The remainder of this chapter is concerned with demonstrating the main points of this thesis. It is structured such as to clarify the following:

- a justification as to why modelling the life cycle inventory is necessary, i.e. the requirement to represent relevant LCI information in an efficient manner
- a justification as to why modelling the life cycle inventory is possible
- the new idea behind the concept
- the relationship of the derived models to the different life cycle stages
- procedure for determining the models
- procedure for carrying out a LCA at the concept stage

Throughout this chapter an electric motor is used for illustration purposes.

[1]Other relevant components are simplified in this study, due to lack of models.

3.2 Assumptions and Definitions

Throughout this thesis the term 'product' refers to parts (e.g. machine element, such as a cylindrical rolling element bearing), subassemblies (such as a set of gears), assemblies (such as an induction motor) or even consumer products (such as a fan or a car) or complex systems (such as a manufacturing line) or all. A product of one manufacturer may be the subassembly to another. It is seen as a relative definition and where necessary this will be clarified. A product consists of components, which are products themselves, and when using the word component, then it infers that in this context it is part of a product. Again it will be clarified where necessary.

At this point it is useful to simplify the life cycle into three distinct phases

1. the pre-use phase, includes the all the phases prior to the use of the product, i.e. material extraction, bulk processing and product manufacture
2. the use phase
3. the post-use phase, includes retirement routes the product undergoes, which may be recycling of materials, components or complete products and the final disposal

This simplified view of the life cycle is further used to argue that the pre-use and post-use phases' inventories of a product

- are proportional to its materials' inventory which depend on
  - the regions where the materials originate and are processed
  - the methods of extracting and processing materials
- and to the product manufacturing and retirement inventory which depend on
  - the regions where the product is produced
  - the methods of production
  - the regions of retirement
  - the methods of retirement

Further assuming that a region's import mix[2] of materials over a given period is constant, an average inventory for a material can be estimated[3]. Consequentially,

[2]From different regions, using different methods of extraction, processing and transportation.

[3]This is not an easy task and may be achieved using macro analysis of material flows into and out of a region combined with an analysis of the individual mines and processing plants of inputs and untreated waste streams per unit output. Material inventory databases present average inventories of materials, but often it is not clear how this value is determined.

when the materials are known for a product, the material related inventory can be approximated.

The manufacturing related inventory of a product can be determined on a factory level. In Section 3.6.1.3 on p. 90 a short description is given. Knowing the manufacturer of the product[4] therefore allows the estimation of the manufacturing inventory. In the case where the specific manufacturer is unknown but the product is known to come from a specific region, the average inventory of all product manufacturers in a region can be determined e.g. using total product production mass as a proportionality factor. If the region is unknown a reasonable alternative is to assume a 'world average', which may be determined in a similar way for a given product.

A further assumption is the notion of a 'representative product'. This is further discussed in Section 3.6.1.2 on p. 88. It must be accepted that all product designs underly physical principals and are limited by material properties and manufacturing methods. These limitations apply to all products.

The differences between corresponding types of products can be traced back to three main sources: differences in the detailed design layout itself, utilising materials with different properties and applying manufacturing methods with different tolerances and reproducibility. The products that are of interest here, were produced for a considerable time and have undergone significant 'evolution', since they first were invented. The product designers must always improve their product with time; usually they cannot continue to sell the same performance and certainly they cannot get worse, otherwise the manufacturer will be out of business in the future. Arguing in this manner leads to the conclusion, that products evolve over time in the sense, that they must become more competitive ('get better'[5]) compared to the previous generation. This trend can be observed in reality.

As manufacturers produce increasingly competitive products — some with greater success than others — within the constraints of the underlying physical principals, material properties and manufacturing methods, some products represent the most

[4] E.g. in cases where the company policy is to uses a preferred supplier.

[5] 'getting better' or becoming more competitive are terms that need clarification: E.g. an internal combustion engine from the 70's is over-designed compared to IC engines today, because in the 70's engineers did have less detailed knowledge about the combustion process itself and did not have as detailed methods to predict the performance, in terms of achieving efficient combustion over a wide operating range and in terms of predicting the stresses due to heat and transmitted forces. Furthermore the manufacturing methods and materials were inferior and less consistent. The lack of knowledge combined with the lack of predictability is the cause of over-design; in the case of the IC-engine this can be seen in a larger engine and a higher fuel consumption for a given power output compared to an IC-engine today with the same power output. Consequentially, 'getting better' in this sense is, that a product performs the intended function more reliably over its design life, while utilising less resources and ideally producing less untreated waste streams over its life cycle.

competitive solution to performing the intended function. The intended function of a product is represented by typical design parameters of that product. The inventory, which is associated with performing that function, is linked to, what in this thesis will be called, life cycle parameters. Some life cycle parameters are linked to design parameters, while others are considered design parameter independent.

Summarising the assumptions in this respect are

1. The manufacturing inventory of a product is presented in relative terms with respect to product mass.

2. The retirement inventory is presented in relative terms with respect to product mass.

3. The product's material composition is presented via a 'representative product'. The actual differences of the relative material composition are small and the consequences on the life cycle are neglected for the purpose of an estimative life cycle assessment.

4. Design parameters are representations of a product's intended function.

5. Life cycle parameters are defined such that they are directly linked to the life cycle inventory.

6. Some life cycle parameters are related to design parameters, while others are design parameter independent.

3.3 Data Representation

With respect to the requirement of relevant data, life cycle design does not differ from any design methods. The data that is required for the analytical process only from the life cycle analysis side rapidly grows into a huge process tree. The LCI of a complex product will consist of thousands of unit processes with 10^4 to 10^5 or more numerical data elements [Bretz 1998]. This emphasises that it is vital to 'compress' information into manageable entities.

A major problem associated with life cycle design (LCD) is that the required data for analysing the life cycle of the concept is either not available for many processes or it is difficult to retrieve the information. A step into the direction of more transparency is the development of a data exchange format by SPOLD[6] that defines the logical structure of LCI data. A network, that provides a prerequisite for the facilitated data

[6]Society for the Promotion of LCA Development

flow, is newly implemented[7]. It is not clear, however, how long it will take until the database is filled with relevant information on a significant number of products and materials. Once this database is running at its full potential and the participating companies and institutions enter and update information on their products, then this is an excellent source for detailed process and inventory data. It is doubtful though that this source is of relevance at the concept design stage, as its high level of detail may render it impractical.

LCD is seen by many as concurrent use of LCA and to draw conclusions from the results of the LCA which may lead to change in the design and eventually to an optimum. This was illustrated to some extent in **Fig. 1.2** (p. 15) where it was shown that the cost of changing the design increases significantly as the design becomes more detailed. Continuous product improvement means — from a life cycle point of view — that the designer has to assess the life cycle of a design and propose changes to the design, which result in improvements to the life cycle of the product. These changes need to be assessed again and the loop continues until the designer is satisfied. As described in Section 2.4 a full LCA comprises, among others, of a Life Cycle Inventory (LCI). Since LCA can be described as being a concurrent part of LCD, any LCD strategy will require a LCI. The development of an integrated life cycle design strategy is aimed at reducing the bulk of information required for carrying out an LCA, but still being able to make valid life cycle design decisions.

The diagram in **Fig. 3.1** shows how the value of information increases with the 'processing' of that information. Therefore the value of the information of the raw data can be further increased if relationships between data and/or parameters are captured by models. The models can be interpreted to describe behaviour and this can be used to form knowledge on which decisions can be based.

The modelling procedure described in the following sections is aimed to increase the value of information in order to make informed life cycle decisions at the concept stage of product design possible.

3.4 Modelling Procedure: An Overview

In **Fig. 3.2** the steps involved are outlined in simple terms. It is shown that the modelling procedure can be divided into three distinct categories:

- Modelling the Life Cycle Parameters (LCPs) against Design Parameters (DPs) (column 'a' in **Fig. 3.2**). It can be shown that for a given product, e.g. an electric motor, the relationship between the design parameter 'torque' and the life cycle

[7] SPOLD Information System (SIS)

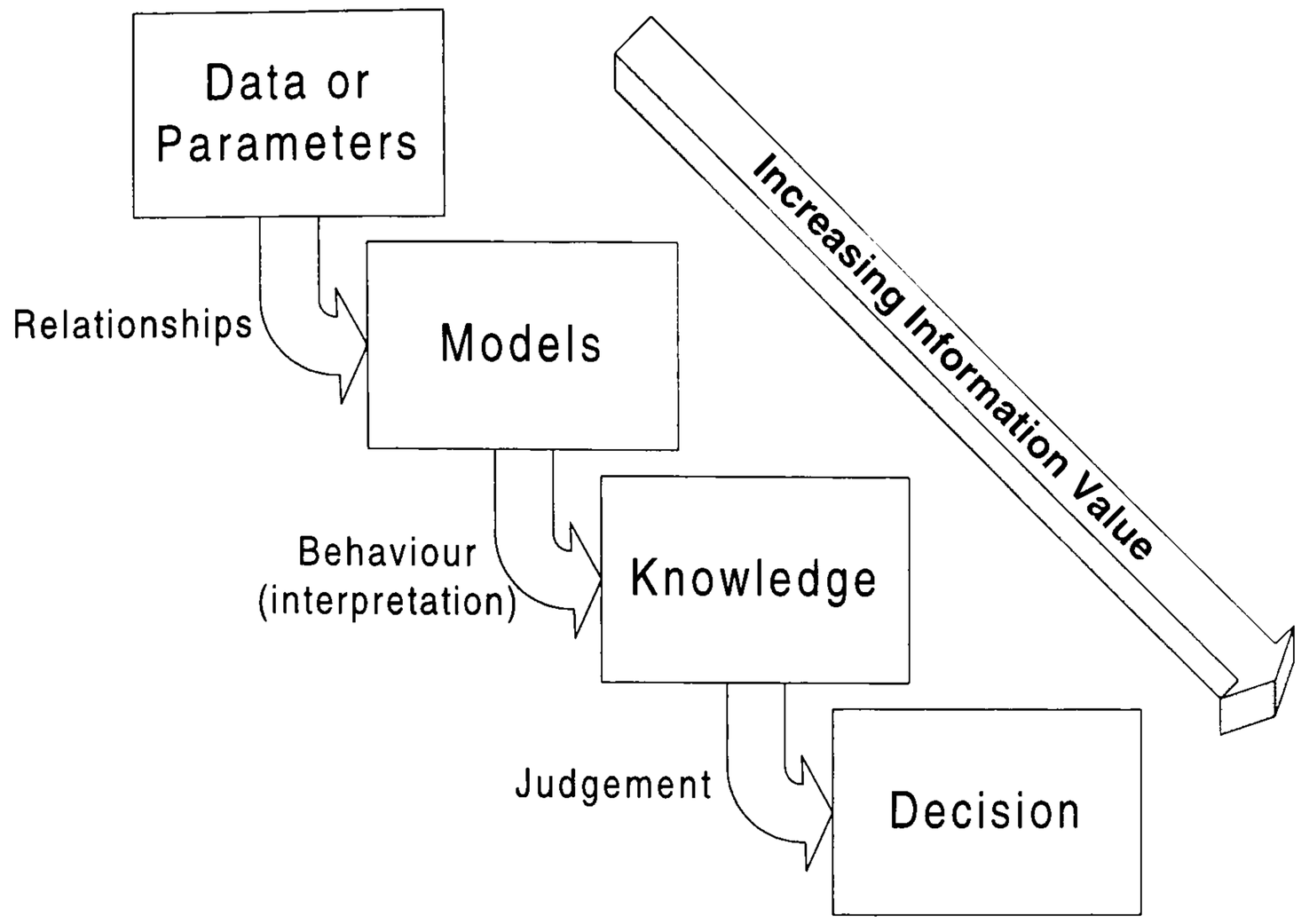


Figure 3.1: The value of information (adapted from [Ullman 1997])

parameter 'mass' can be expressed as a function, in simple terms: the higher the required torque the higher the mass.

- Modelling the inventory as a function of the LCPs (column 'b' in **Fig. 3.2**) E.g. some life cycle parameters of an electric motor are its 'mass' (and related material composition) and 'efficiency', as these parameters have a strong relationship to the life cycle inventory.

- Using the models to carry out an 'order-of-magnitude' LCA suitable for evaluation at the concept stage of the design process (column 'c' in **Fig. 3.2**). E.g. when a designer has to choose between different electric motors at the concept stage, then from the designers point of view the design parameters are 'torque', 'speed', 'start-up characteristics', etc.. These parameters can be more easily estimated than the inventory data. The relationship between the DPs and the LCPs (see first point) is used to determine the life cycle inventory, which is used, in turn, to carry out an estimative LCA.

In the following sections each step is described in more detail.

3.5 Modelling Design Parameters against Life Cycle Parameters

This Section is concerned with describing the main concept behind the method of estimating the life cycle inventory, which is being developed as part of this work. The beginnings of this work were briefly described in [Mueller, Court & Besant

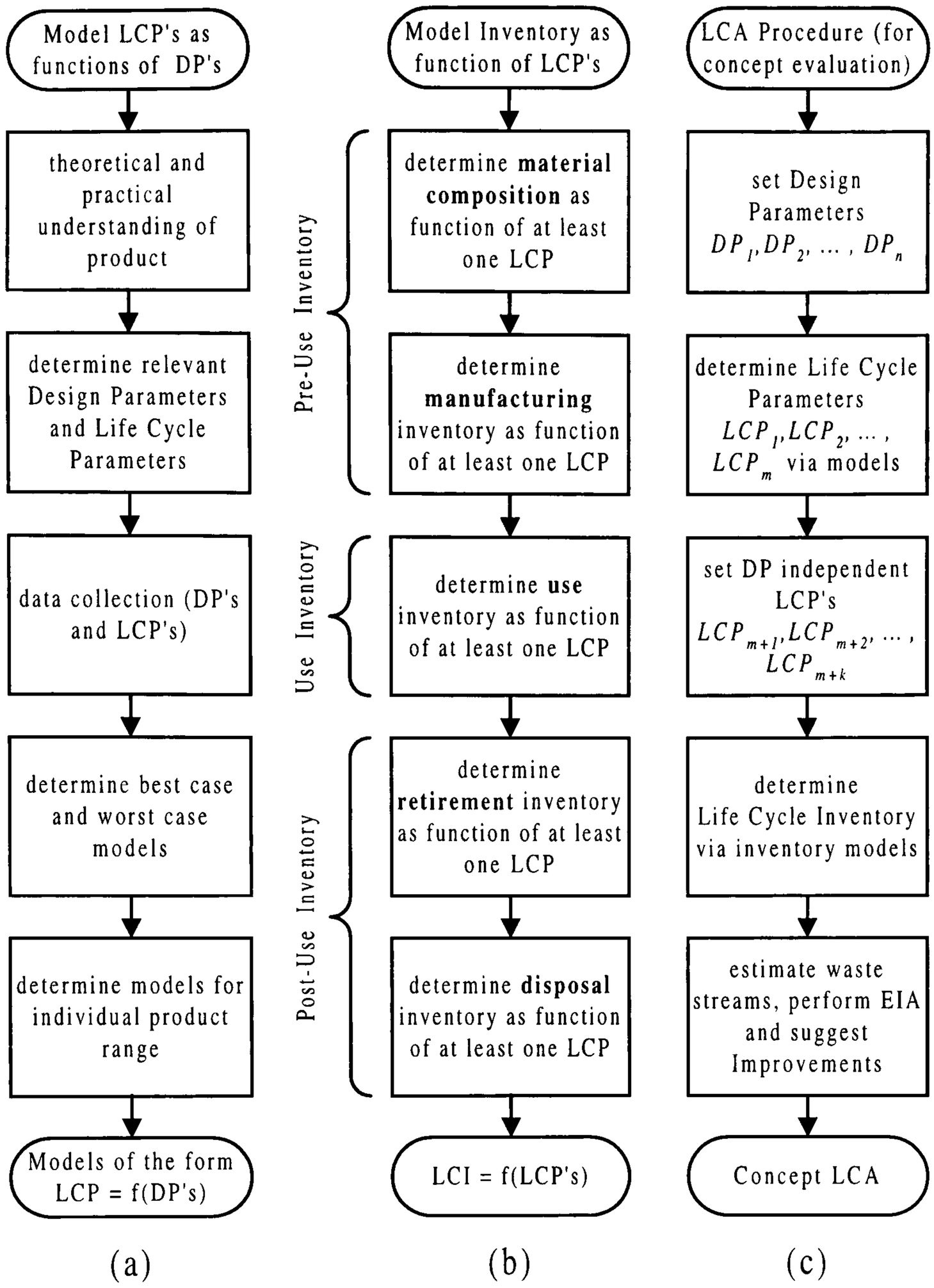


Figure 3.2: Flow charts illustrating the procedure for (a) modelling the LCPs as functions of DPs; (b) linking the LCPs to the inventory (c) carrying out a LCA at the concept stage

1998, Mueller & Besant 1999]. An obvious method for condensing vast amounts of information into manageable entities is the use of existing relationships which can be described by mathematical equations. These relationships are determined by modelling characteristic *design parameters* against *life cycle parameters* (see Section 3.5.2.1 and Section 3.5.2.2). Initially the format of the relationships have to be proposed. This requires assumptions, which are based on

- theoretical reasoning
- common practice and practical considerations (e.g. due to standardisation)
- empirical observations

or combinations of the above. Once the life cycle parameters ($LCPs$) are related to the design parameters (DPs) in the form of

$$LCP = f(DP_1, DP_2, \cdots, DP_n) \tag{3.1}$$

the life cycle parameters can be optimised by choosing different combinations of the design parameters.

The procedure is in some respect similar to a costing method, where the cost is scaled according to the output parameters (such as energy output of a heater, mass flow and pressure of a pump, etc.). The costing method was briefly described in Section 2.6.5 (p. 60).

3.5.1 Theoretical and Practical Understanding

When attempting to finding out how to best represent the LCPs in terms of DPs then it is most important that the analyst not only understands total life cycle design, but also knows the product that is being modelled to such an extent, that he understands what the DP's relationship is to the functional requirement of the product and how a product scales with different requirements.

A detailed analysis of a product may reveal theoretical relationships between functional requirements, DPs and LCPs. Theoretical relationships are a useful starting point when proposing what to model. The good choice of DPs and LCPs is a requirement to find meaningful relationships. A good choice ensures that not too many DPs are used to flow into the relationships, as this would complicate the modelling without being of benefit and in the worst case making the models unrealistic. It would further increase complexity at a later point, when using the models for LCA, i.e. when the designer needs to estimate the DPs.

This method depends on modelling not only an individual product of a particular size and with particular options, but a whole product range. For this reason it is important that the analyst pays particular attention to what extent the options influence the LCPs and what effect the scale has on the the LCPs. There may e.g. be a sudden change of the LCPs for small change of the corresponding DP. This may have to do with standardisation and with the fact that small versions of a product are manufactured in different ways to large versions of the same product, which in turn may be dictated by economic considerations (smaller version of the products are usually sold in larger quantities compared to the larger version products) or with technical and physical constraints (as a product is scaled up, the technical and physical constraints may not scale up at the same ratio).

3.5.2 Determining Relevant DPs and LCPs

3.5.2.1 Design Parameters (DPs)

Design parameters (DPs) are usually physical characteristics of the design of a machine element or assembly. The DPs, which are interesting within this context, have to fulfil the following criteria:

- The DPs have to be parameters that can be *estimated* at the early phase of designing. E.g. the power output of an electric motor can be estimated at an early stage, but, say, the physical dimensions that the motor must have are less obvious at this stage.

- The DPs must have a *significant relationship* to at least one life cycle parameter. E.g. whether the casing of a machine is painted red or blue can be decided early during design, but it most probably bears little impact on the life cycle. On the other hand whether the design is painted (or treated) at all, and if so, with which type of paint, will most probably influence the life cycle parameters.

Typical DPs include (output-)parameters for assemblies such as:

POWER OUTPUT AND OPERATING SPEED of an electric motor are characteristic measures for its size.

VOLUMETRIC FLOW RATE is a characteristic measures for the size of a pump.

TRANSMITTED FORCE AND TORQUE for machine elements and the resulting

DIMENSIONS AND MATERIAL PROPERTIES to support the force and torque.

SURFACE FINISH determines among other parameters what manufacturing process has to be used.

The degree of accuracy with which the DPs can be estimated, must be monitored as part of the overall design procedure. The effect of individual DPs on the overall result can be analysed to see the relative importance of the individual DP.

3.5.2.2 Life Cycle Parameters (LCPs)

Life cycle parameters are defined as parameters that relate directly to the life cycle inventory of one or more life cycle stages. LCPs are not limited to a particular class of parameter, and includes physical parameters, temporal parameters and discrete (quantitative and qualitative) parameters.

LCPs should fulfil the following criteria:

- The LCPs main criteria is that they relate to part of the LCI. Ideally this means, determining and/or specifying values of *all* the relevant LCPs of a product, then a LCI can be determined with general inventory data on materials and energy generation.

- Values for LCPs should be obtained from publicly accessible data sources. This means that the manufacturing industry itself or third parties have an active interest in publishing this data or the data can be indirectly derived through established relationships to published data. It is of little use if the LCP is of a nature that product manufacturers are unable to supply data on the grounds of confidentiality or similar issues.

- Some LCPs are related to DPs. The relationship can be of a continuous, semi-continuous (e.g. due to standardisation) or discrete nature.

- DPs are not excluded and may also represent LCPs.

- If the LCPs are described by qualitative data then these discrete levels should be limited to a sensible number by making assumptions.

Examples of LCPs are:

MASS of the product (or material) is proportional to the materials required to manufacture the product, i.e. it can be directly linked to the pre-manufacturing phase. Furthermore it will influence considerably all the other life cycle phases.

MANUFACTURING METHODS have their impact on the manufacturing phase of the life cycle.

SURFACE TREATMENT influence the manufacturing and usage phase.

EFFICIENCY predominantly influences the usage phase and may have an influence on the pre-use inventory.

USAGE CHARACTERISTICS AND DESIGN LIFE are important to determine the relative importance of the usage phase.

MAINTENANCE AND UPGRADEABILITY CHARACTERISTICS are relevant to the usage phase.

RETIREMENT AND DISPOSAL CHARACTERISTICS are linked to post-use phase of the product.

Not all LCPs are dependent on DPs, some are constant for the whole range of DPs. This is not disadvantageous as it simplifies the process.

An example of an DP-independent LCP is the retirement strategy, i.e. how much of the product is going to be reused, remanufactured etc.. It is a percentage that may be fixed for the whole product range, on the other hand, it may be practical to remanufacture larger products and to recycle smaller products of the same range. Then the LCP is DP-dependent, but this can be captured by specifying an appropriate model.

Another DP-independent LCP is the anticipated actual time of use of a product. It may have a large impact on the life cycle, but it does not have to depend on design parameters. On the other hand, the use-time may depend on, say the size, in such a manner that the bigger the machine the faster it can do a particular job. Then the use-time is not a DP-independent LCP, but this too, can be incorporated as a relationship.

3.5.3 Data Collection

The data collection process will take up a considerable time when developing the models. This may be helped considerably through collaborating with companies who often have the required data in electronic form.

There are various sources of data on the DPs and LCPs that can be utilised. These include mainly

- Manufacturer information, i.e. printed or electronic catalogues or directly supplied data
- Technical product literature
- Third party database, which include data on multiple manufacturer

Another method of obtaining data would be to test and disassemble an actual product range, but the time and cost constraints have to be considered. The data is required for a large amount of products within a product range and from many manufacturers. Therefore this method is unsuitable in this context.

3.5.4 Modelling the Upper and Lower Limits

The next step of this method is to determine upper and lower limits of the LCPs in terms of the DPs. In the case where the LCPs and the DPs are selected correctly, i.e. that there is a relationship between the two, then a banded region can be observed, as is illustrated in **Fig. 3.3**.

Here the x-axis is designated with a DP. In general it may also be a combination of DPs, e.g. instead of LCP only depending on the DP 'Torque', the LCP may depend on a combination of DPs, such as 'Speed' times 'Torque' (= 'Power').

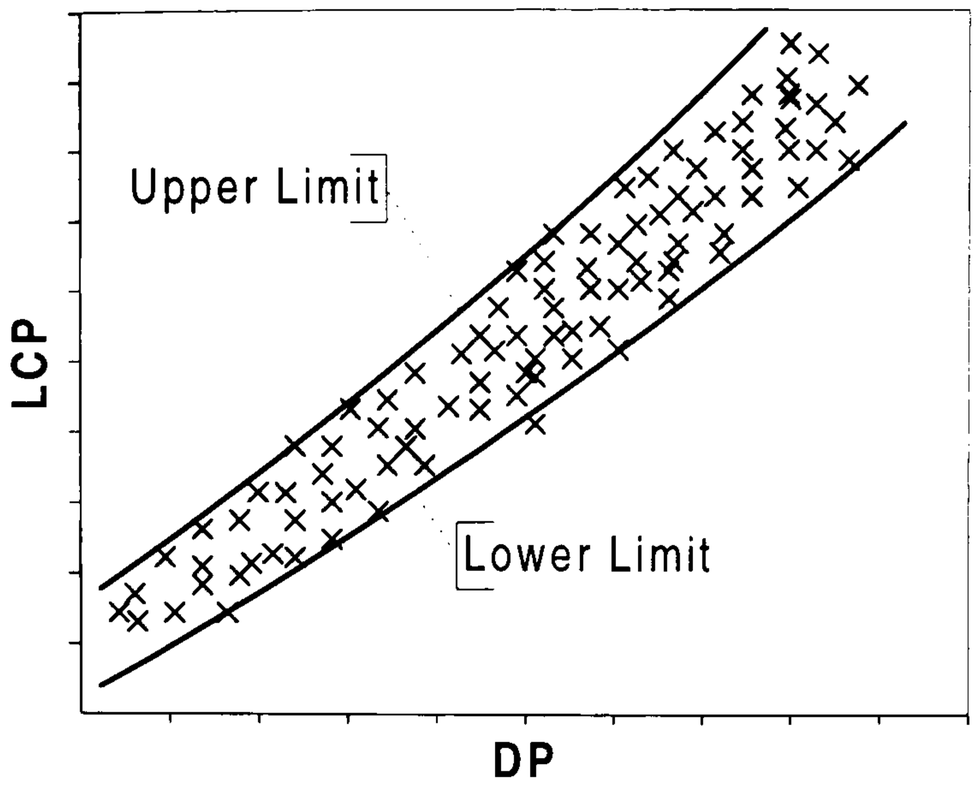


Figure 3.3: Schematic illustration how data (crosses) are banded, so that an upper and lower limit can be determined

When mentioning upper and lower limits, it is possible to qualify the upper and lower limits depending on what the actual LCP is and how critical that LCP is on the total life cycle. By this it is meant that one line represents a *best case* and one a *worst case*. For example, if the LCP is mass and mass is a critical issue of the life cycle, then the upper limit is the worst case. On the other hand the lower limit represents the best case, i.e. for a given DP the minimum mass (the LCP) is represented by the lower limit.

Usually the line representing the upper and lower limit cannot be related to theoretical considerations about the relationship of the DP and the LCP. But theoretical considerations offer a good start for the initial guess of the form of the equation.

The initial form of the equation may then be adapted on an empirical basis to include

- less terms, by excluding the terms with little statistical significance regarding the model or
- further terms, if the fit is not sufficient to capture the trend of the data

The upper and lower limits models can be determined for groups of data, such as to a product range of a manufacturer or indeed to all the products, describing the upper and lower limits of what is actually produced.

3.5.4.1 Procedure

The modelling of the upper and lower limits is carried out by extracting from the multitude of data the points that represent the extreme positions and then use these points to fit a model that represents an upper limit of what is available and a model that represents a lower limit.

These limits capture the actual solutions of what technical products are able to provide at this moment in time with respect to the DPs and LCPs. If a designer wishes to

explore the future he may estimate how much the features improve and shift the models in the direction of an improving LCP.

3.5.4.2 Further Refinement

Establishing the aforementioned relationships between DPs and LCPs it is important to realise that they should

1. correctly summarise the facts and
2. be simple enough for practical application.

This is true for any scientific law and in this paragraph it is expanded upon with respect to this thesis.

In order to increase the accuracy of the relationships, the models may be expanded by including further DPs to describe a LCP. In **Fig. 3.4** the data is shown to be banded in three distinct narrower bands. These represent a second DP's influence which can be incorporated into the model to give a more detailed representation of the LCP.

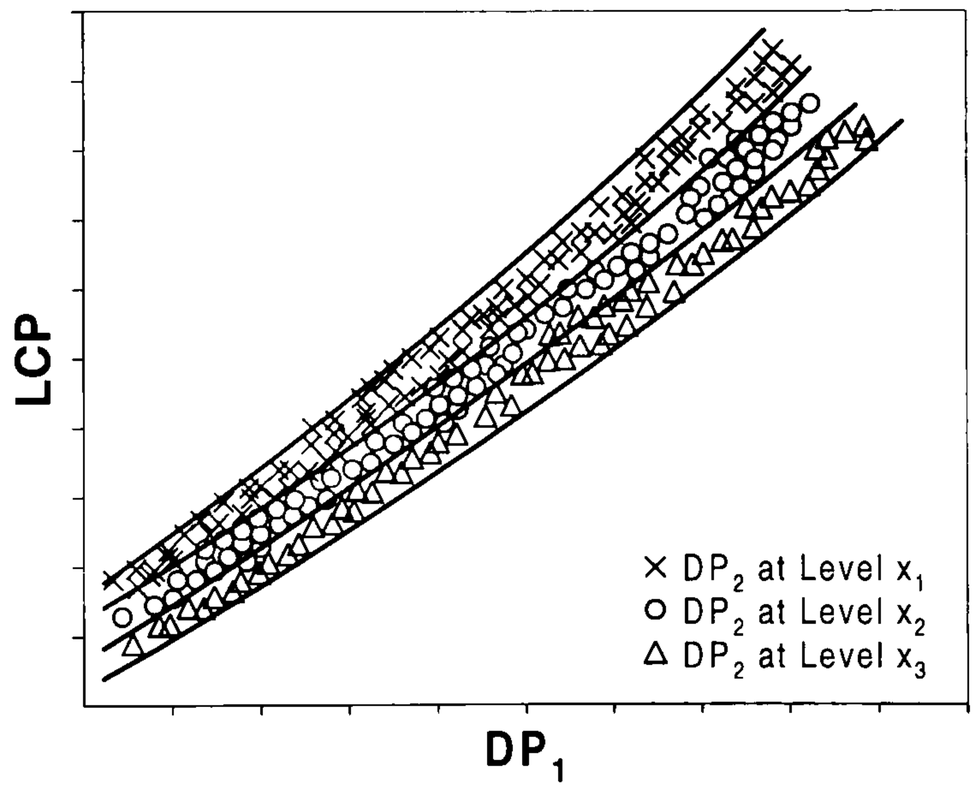


Figure 3.4: Schematic illustration how data depends on a further DP, which can be used for a more accurate grouping

In **Fig. 3.5** the band is narrower altogether since the LCP is plotted not against one DP, but against a function of DP_1 and DP_2.

This may be repeated with further DPs to obtain more refined models. The validity of the other models is not compromised by this and they should be kept, as they represent the LCPs when not all the DPs are known.

This is a strength of this method in that it always offers a compromise between simplicity and accuracy. When a DP can be estimated then it enables to more estimate the LCP. This is a useful feature for the continuous design process, i.e. as the design progresses and more DPs are fixed the more accurately the LCP can be estimated.

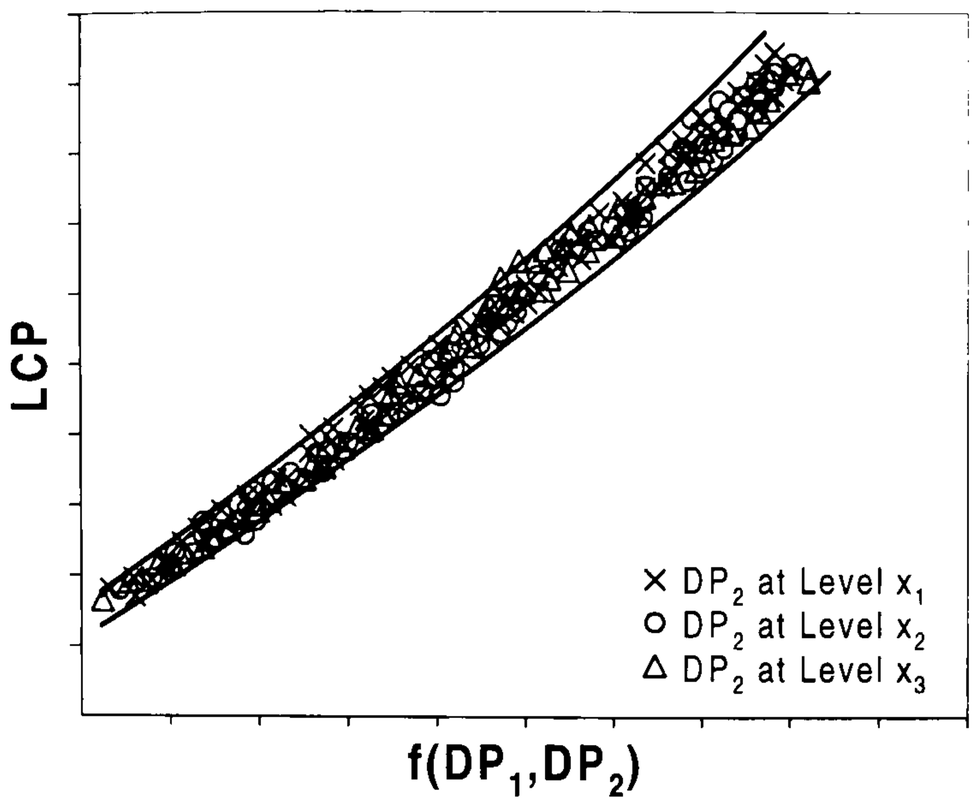


Figure 3.5: Schematic illustration of how the LCP is not plotted as a function of one DP but as a function of DPs

3.5.5 Modelling One Manufacturer's Product Range

When looking at the data of *one model range* of *one manufacturer* then it can be observed that the points lie in a much closer band, which can be represented with one fit for the whole range. This is illustrated in **Fig. 3.6**.

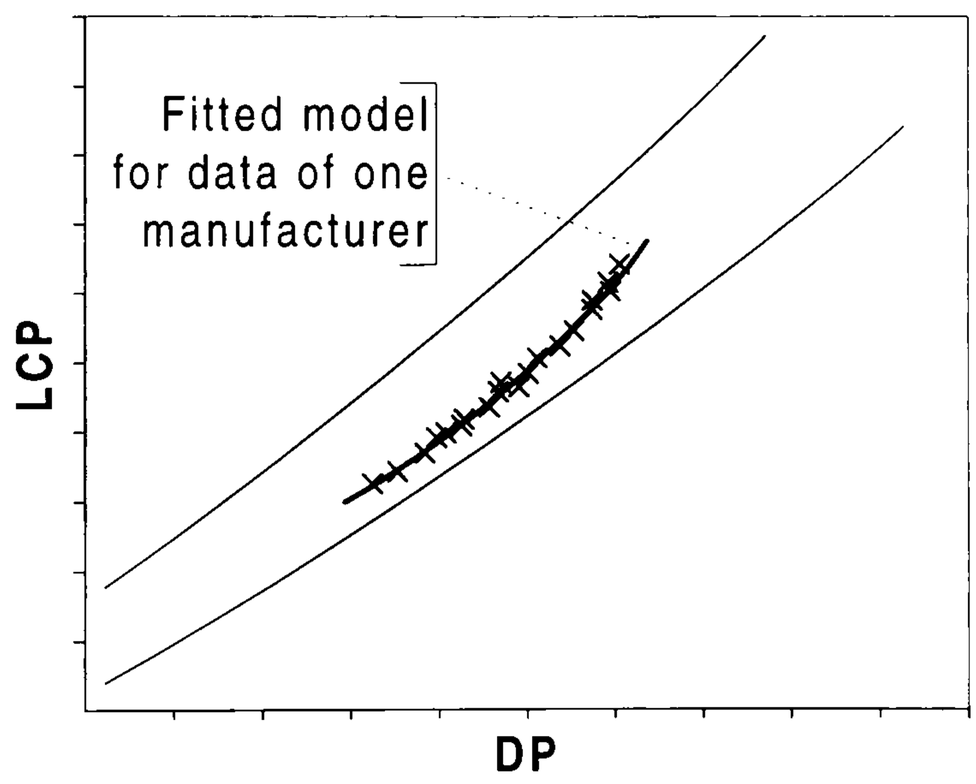


Figure 3.6: Schematic illustration how data (crosses) of one manufacturer's product range lie in a much tighter band, which may be represented by one model

Furthermore the graph in **Fig. 3.6** illustrates that the model if the individual product range does not necessarily follow a line parallel to the lines representing upper or lower limit. It follows a line which is dictated by the actual realisation of a product by a manufacturer. Therefore the models of the individual product range can be quite different to the models representing the upper or lower limits.

This information may be useful to compare in general terms different product ranges of one or several manufacturers, but the additional work that is required to generate the models is considerable.

The aforementioned also applies to modelling the characteristics of a *single product*, in cases where the DPs are more complexly related.

3.5.6 Types of LCP vs. DPs Models

Once the models are established it may be interesting to compare how the models relate to sets of data of real products. A comparison may be carried out in relative terms, such as the ratio of actual value over the modelled value. In this context it is useful to compare more generic models (such as the best of a range, or the overall best) with specific data sets, and specific models with their respective specific data sets. Comparison may be carried out by evaluating the mean and standard deviation to indicate where in relationship to the different models the product data lies and how wide the range is of the product range. At this point it is useful to define names to the different models. They are distinguished as follows:

- specific product model (SPM) (modelling a single product, Section 3.5.5),
- specific product range model (SPRM) (modelling a product range from one manufacturer, Section 3.5.5),
- Lower limit / upper limit specific product range model (LLSPRM, ULSPRM), capturing the lower and upper limits of several products in one product range from one manufacturer (Section 3.5.4) and
- Lower limit / upper limit generic product range model (LLGPRM, ULGPRM), capturing the lower and upper limits for a large number of products from many product ranges from several manufacturer (Section 3.5.4).

The different types of models represent different levels of abstraction and have to be viewed with this in mind. This means that there is not necessarily a product range that, say, follows the lower limit generic product range model, but it is more likely that in a product range some products have characteristics similar to the LLGPRM, but only within a specific DP-range, and another product range coincides with the LLGPRM for a different DP-range, etc. Consequentially the LLGPRM is a model that represents data from various products, from several product ranges and manufacturers. The same applies to the ULGPRM and the principle is schematically illustrated in **Fig. 3.7**.

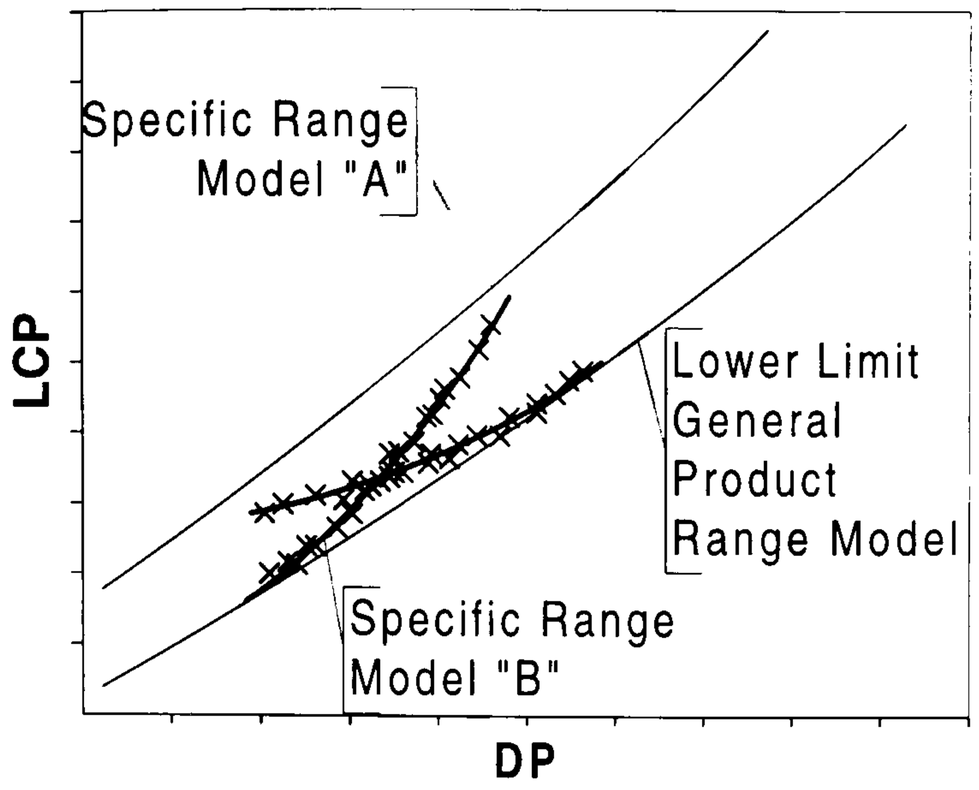


Figure 3.7: Schematic illustration how the "A" product range coincides with the LLGPRM for certain DP-range only, and the "B" product range coincides with the LLGPRM for a different DP-range.

3.6 Modelling the Life Cycle Inventory against the Life Cycle Parameters

Life Cycle Inventory Data Obtaining the life cycle inventory is regularly the most work intensive part of any LCA, mainly because it is extremely difficult to automatise this task. It follows that any reduction in the workload associated with putting together the inventory will make LCA more suitable for assessing the life cycle at the concept design phase.

LCI data of a product typically consists of the names and masses for the

- engineering materials that make up the product and that are wasted because of process inefficiencies, whereby some of the materials may be returned to the process at some later stage (recycling);
- auxiliary materials (including materials used as fuels) associated with the various processes of the different life cycle stages;
- airborne, waterborne and solid residuals associated with various processes of the different life cycle stages.
- some forms of electromagnetic radiation

In the following sections the inventory of the different life cycle phases is looked into.

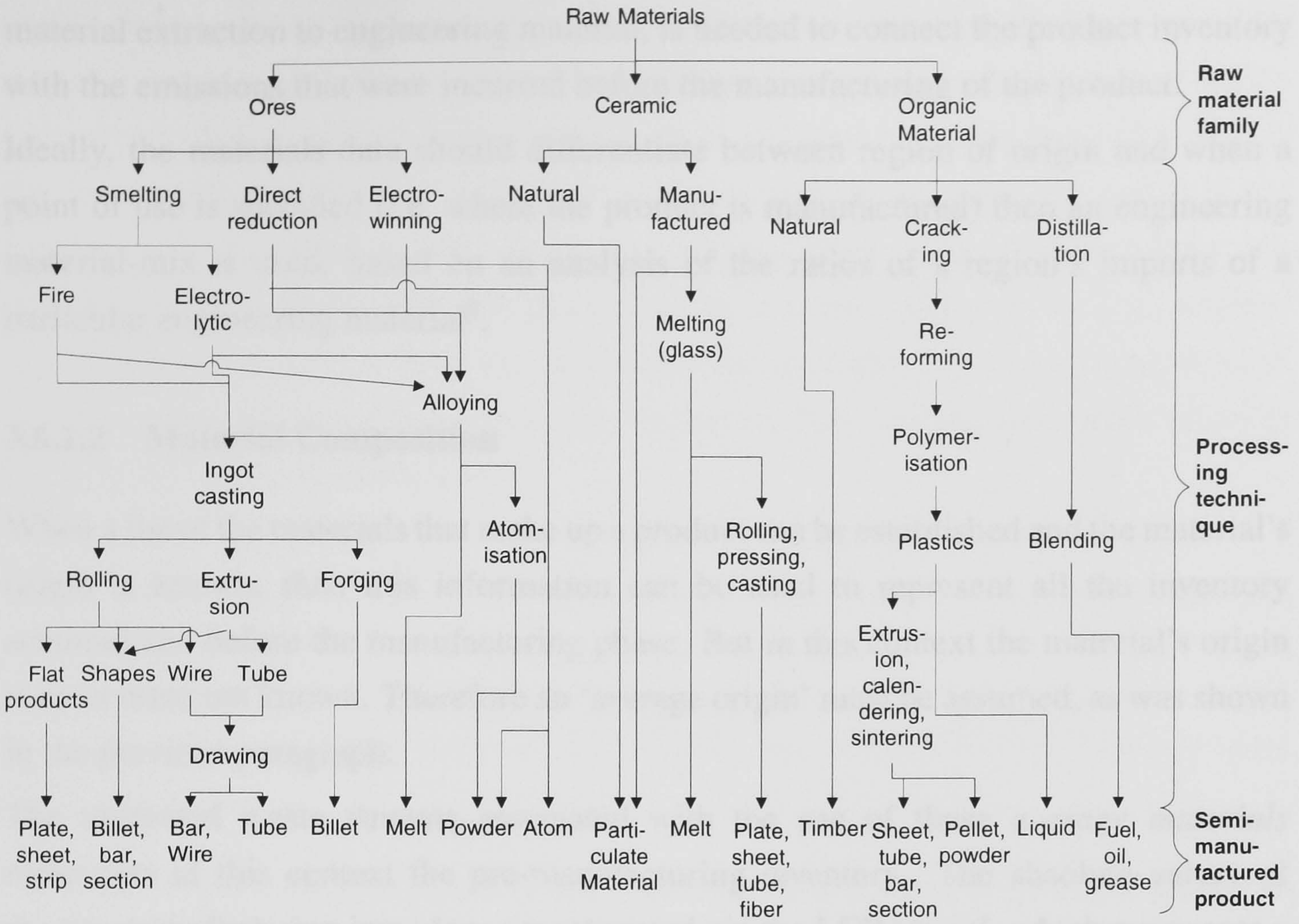


Figure 3.8: Engineering materials are semi-manufactured products, which undergo a series of processes to be extracted from the raw materials (adapted from [Schey 1987])

3.6.1 Pre-Use Inventory Data

The life cycle stages covered in this section are those that precede the use phase, i.e. the extraction of the raw materials, the manufacture of the engineering materials and the manufacture of the product itself.

3.6.1.1 Engineering Materials

The materials that are used to make components and products were made some time before. Emissions and energy requirements occur during the raw material extraction, bulk processing of the raw material and during transportation of the raw material (or of the raw material, in cases where the bulk processing occurs at a distance from the raw material extraction site). In **Fig. 3.8** a selection of processes are included to illustrate what is required for raw materials to be transformed into engineering materials.

This chart demonstrates that there are 3 families of raw materials which end up in about 16 types of semi-manufactured goods (engineering materials). The raw materials undergo between zero and 5 processing techniques. An engineering materials database, that includes information on untreated waste streams for all the stages from raw

material extraction to engineering material, is needed to connect the product inventory with the emissions that were incurred before the manufacturing of the product.

Ideally, the materials data should differentiate between region of origin and when a point of use is specified (i.e. where the product is manufactured) then an engineering material-mix is used, based on an analysis of the ratios of a region's imports of a particular engineering material[8].

3.6.1.2 Material Composition

When a list of the materials that make up a product can be established and the material's origin is known, then this information can be used to represent all the inventory accumulated before the manufacturing phase. But in this context the material's origin is most often not known. Therefore an 'average origin' must be assumed, as was shown in the previous paragraph.

The untreated waste streams associated with the use of these *average materials* represents in this context the pre-manufacturing inventory. The absolute values of the pre-manufacturing inventory are estimated via the LCP 'mass', which represents a proportionality factor.

Representative Product An assumption of this thesis is, that each product may be represented by a typical *representative product*, which is not fixed in size, but is scaled according to suitable design parameters.

A typical product is defined here to include the most common features and the most common implementation of achieving the function. These features scale in proportion to the design parameters.

The representative product is determined by analysing a product range, that is based on the same working principle, from various manufacturers and determining the common implementations and either 'averaging out' different implementations or, if the differences are large, then they should be listed as products working according to the same principle, but with different features. The criterion for the averaging include

- most technically successful solution
- most commercially successful solution

Representing the product in the aforementioned manner, leads to the requirement of choosing suitable design parameters. This was discussed in Section 3.5.2.1. Here it

[8]This means that for a given period it may be possible to state for a region where the imported materials originate. E.g. in 1996 Europe imported 50% of the Copper from Chile, 30% from Zambia and 20% from Australia (number are for demonstration only).

should only be mentioned, that the representation of information relating to the LCI (see also Section 3.5.2.2) with respect to the design parameter or combination of design parameter will highlight an *actual industry-best* and an *actual industry-worst*. This is the level of detail suitable for analysis at the concept stage, meaning that it is not required to know which specific product of which company has what properties, but it is important to know how one technology as a whole compares to, e.g., another technology that is able to fulfil the same function. In addition to this an evaluation of the *industry-average* can be carried out, by looking how leading companies relate to the industry-best and industry-worst.

Applicability In cases where a product is made of a number of materials, then the assumption is that

- the relative material composition changes only slightly for the whole product range
- the material composition does not vary significantly between different manufacturers, because of technical constraints

Materials are chosen to balance the functional requirements of the product, manufacturing and other cost criteria. When investigating a product range from different manufacturers it may be found that certain materials or material combinations predominate the product range as a whole and that their absolute content scales with the size of the product.

In cases where the relative material composition varies for one type of product the factors why this occurs need to be investigated. Factors influencing the material composition may be due to different

- technical solutions to the underlying problem
- quality of products (i.e. for different applications and different types of customers)

In these cases the different material composition needs to be distinguished.

Advantages As indicated the advantages of representing the life cycle information in this manner lie in representing information at a level of detail that is suitable for concept design decision making. Further advantages include

- data that is required can usually be found in product catalogues, CD-ROM's or third-party databases

- significant reduction of data
- future trends can be incorporated by anticipating changes in performance, i.e. by changing the relationship of DPs to LCPs
- truly innovative products 'stick out'

Disadvantages and Limitations The limitations of this method is that representing an average product, means that the real product may not at all have the assumed material composition. This emphasises the need for carrying out a more complete LCA at a later stage of the design phase to re-cheque the assumptions made during the early LCA. The assumptions include the relative material composition.

A problem associated with this method is that in order to obtain meaningful information a large amount of data is required from various manufacturers.

In summary it may be said that the disadvantages and limitations are

- the requirement of rechecking the LCA at a later stage to make sure that the assumptions (such as relative material composition) were correct,
- the requirement of large amount of data from many manufacturers to generate the models.

Practical experience has further shown that liaising with non-technical sales personnel to supply the requested information tends to have a prolonging effect on obtaining the *actually required* data.

3.6.1.3 Manufacturing Phase Inventory Data

A detailed method for gathering inventory data is on a process basis (micro analysis), i.e. if a process A is used then x amount of material α is used, etc.. Knowing how much of a product a is produced during the operation of process A, then we may allocate a proportion of the inventory to the production of a. This is a very work intensive work and does not suit the *low detail* that characterises concept design; it would present 'data overkill' in this context.

Taking into account the required level of detail and practical considerations, it is proposed here that looking at the inventory at the *factory level* (the 'system' in **Fig. 2.4**, p. 29) is most practical for the following reasons:

- much of the data is collected anyway as part of accounting procedures and to comply with environmental legislation

- often companies publish relevant inventory data at this level in their environmental reports (which are themselves becoming more popular)
- production output of the factories are often published as part of the annual reports, thus allowing an allocation of the inventory to the product
- if relevant data is collected within a company, it is more likely to gain access to such data
- allocation of the inventory to a product (or product range) can be achieved by using proportionality factors such as total production mass
- the inventory of a product can be represented in relative terms, e.g. per unit weight
- relative product inventory data from several factories of a region can be averaged to represent a regional average product

As with previous phases, the *relative* manufacturing inventory (e.g. per unit mass of products) is used to determine absolute values.

3.6.2 Use Inventory Data

When looking at the inventory associated with the use of the product then it is useful to distinguished between *active* and *passive* products.

Active products convert energy from one form to another as part of their function and therefore inherent to their use. Examples are bearings (mechanical to heat), electric motors (electrical to mechanical and heat), heaters (electrical or chemical to heat), microwave ovens (electrical to electromagnetical to heat) etc..

Passive products are not directly involved in the aforementioned energy conversion. Examples are bridges, cups, windows, towels, paper etc..

The use inventory is split into two categories:

1. direct use inventory
2. indirect use inventory

Direct Use Inventory It is that part of the inventory that is incurred at the time of use by the product, i.e. when the product is active. Therefore, a passive product, by this definition, does not directly incur inventory. The direct use inventory is usually a form of energy or a fuel, but can be anything that is used as a direct result of use, such as lubrication oil in an engine. LCPs relating to the direct use inventory are, e.g., efficiency, usage times, input or output power, etc.

Indirect Use Inventory It is the part of the inventory that is required to support the product, such as inventory due to maintenance, inventory due to modifying the environment to suit the product (e.g. heating, cooling, changing humidity, etc.). Characteristic for the indirect use inventory is that if the support did not exist, then the existence of the product would be impossible or not make sense.

3.6.3 Post-Use Inventory Data

The post-use inventory covers all the stages after the product has reached the end of its useful life.

3.6.3.1 Retirement Inventory

The retirement strategies can be one of the recycling loops (both closed loop and open loop), i.e.

- reuse
- remanufacture
- recycling or

or

- disposal

The inventory associated with each of these routes is related then to a LCP. An appropriate LCP is mass, i.e. to allocate the inventory associated with reuse proportional to mass and the inventory associated with remanufacture proportional to mass, etc..

The retirement strategy, or, more appropriately, the combination of retirement strategies for a product range, is also an LCP which needs to be specified. This is specified by estimating the percentage of the whole product range that undergoes each retirement route. These estimates can be based on historical data and by varying these percentages it is possible to see the overall impact of changing the proportion of each route.

3.6.3.2 Disposal Inventory

Disposal is the final life cycle stage a product undergoes. It may involve treatment of the product to reduce the negative effects.

The disposal inventory describes the required inventory to completely dispose of the product. Possible disposal scenarios are

- landfill (i.e. solid state)
- combustion (i.e. gaseous state)
- river and sea disposal (i.e. liquid state)
- other variants (e.g. deep mine disposal, deep sea disposal)

This is related to a LCP by a proportionality constant, i.e. the LCP may be mass and the inventory is allocated according to the mass of the product.

The disposal scenario is also expressed as a percentage combination of the possible routes, and this is a LCP that needs to be specified.

3.7 LCA Procedure

In this section the procedure to carry out an LCA using the aforementioned models is described. It will become apparent, that the effort required for establishing the LCI is substantially reduced compared to conventional methods.

This procedure is the only part of the whole method that the designer 'sees'. The designer does not need to know what the actual individual models are, but only requires information on the applicability, assumptions and limits of the models. They may be otherwise hidden in a 'black box' and still be of use for obtaining relevant life cycle information on a concept. The designer only needs to specify the DPs and the DP-independent LCPs.

3.7.1 Setting the DPs and determining the LCPs

Firstly the designer estimates the DPs, that can be estimated at the early stage of the design process. Estimation may be based on previous solutions to similar problems or estimate layout calculations.

As the design progresses they may be reevaluated for control purposes. It is always a good idea to check the assumption made at the beginning of the LCA, at some point later.

Depending on what DPs can be estimated, the relevant LCPs may be found to more or less accuracy. In a software implementation this procedure may be hidden and the designer only sees the resulting LCP, which can vary depending on the type of model chosen (e.g. ULGPRM, ULSPRM, see Section 3.5.6, p. 85), or it may only be necessary to show the resulting life cycle inventory. It must be decided depending on what detail is required.

There are also LCP which do not depend on DP's and need to be set for a complete LCA. This information includes such LCPs as retirement strategy and design life of a product.

3.7.2 Determining the Life Cycle Inventory

After the aforementioned steps the LCA analyst is able to determine a complete LCI. This LCI must be treated as an estimate LCI which can be used further to complete a estimate LCA. It is aimed to highlight the most important stages of a design, and to show strengths and weaknesses of a concept, which can be compared to another concept.

The LCI was linked to the LCPs as was shown in Section 3.6. This, too, enables the implementation of the method into a software, which can be used to go directly from the DP's to the LCI and only showing the most important LCPs. There are many possibilities for the actual implementation, depending on the end user's expertise, different levels of transparency can be utilised.

3.7.3 Completing the LCA

The final step for the complete LCA is linking the LCI to the environmental impact assessment (EIA) and to the improvement phase, where the conclusions are drawn from the EIA. These two steps are no different in this methodology than current methods for carrying out LCAs and indeed this method can be easily adapted to any EIA-method.

The method described here supplies the LCA analyst with an order-of-magnitude LCI of a product, which is required as an input to any LCA. Determining the LCI of a product is the most time consuming part of LCA and therefore this method represents large time saving potentials where they are most required from a designers point of view.

Whatever the interpretation is of the chemical's impact, it is believed that it is important to list those chemicals, that are today seen to be responsible for the largest part of the environmental impact, in such a way, that the designer can see which chemicals are attributed to which life cycle stage and component. This will highlight in many cases the sensitive phase of the product and thus allow the designer to focus on this area. The main chemicals, that should be listed, are

- Carbon Dioxide, CO_2 and CO_2-equivalents over a 20 year horizon, mainly resulting in global warming due to greenhouse effect
- Sulphur Dioxide, SO_2, causes winter smog and acidification

- Nitrogen Oxides, NO_x, causes acidification and eutrophication
- Chlorofluorocarbon compounds (CFC), mainly causing the depletion of the ozone in the stratosphere
- Volatile organic compounds (VOC), is mainly responsible for summer smog
- Heavy Metals (e.g. Cadmium and Lead), regional long term contamination of the environment and in the long term enters the food chain at which end we are consumers
- Dust, causes winter smog
- Phosphorous compounds, causes eutrophication

and as a general indicator the

- Gross energy requirements

This will allow a quick overview and is of value, especially if a concept is superior with respect to the emissions in all phases, then a decision can be made.

After looking at the chemical inventory a normalisation and weighting method should be applied, especially in cases where the conclusion from looking at the absolute chemical data values is ambiguous.

3.8 Life Cycle Costing

The possibility of adding a monetary evaluation procedure within this method is seen as a further advantage. Here only a short discussion is given, but it highlights that the structure of how the data is represented aids the inclusion of costing methods, especially scaling using product weight (Section 2.6.1) and scaling using material cost (Section 2.6.2).

The product weight is a modelled LCP and therefore scaling based on the product weight is a matter of obtaining current relative product cost data. This method is relatively crude (see Section 2.6.1), but practical and often used in industry.

The relative material composition together with the LCP 'mass' gives an estimate of the absolute mass of the materials used. This can be used to estimate the material cost of the product and with data on the percentage share of the material cost of the overall product cost, the overall product cost can be estimated (see Section 2.6.2).

The possibility of including more detailed costing methods described in Section 2.6 requires further analysis.

Estimating the cost of the components in relationship to LCPs, which in turn are modelled as functions of DPs, links the cost to design parameters. An integrated implementation of costing[9] thus allows the designer to estimate the cost of changing of DPs on the overall life cycle cost.

3.9 Sensitivity in Modelling

There are two main sources of inaccuracy with respect of what the model predicts and what the experience is in reality. They are

INHERENT MODEL INACCURACY All models have assumptions associated with them. As a consequence the results from a model cannot be expected to perfectly model the reality. Ideally the range of applicability of the model as well as the expected range of error should be known.

The inherent model inaccuracies are even more relevant when attempting to assess the design in the early stages of design. At this stage the design itself is not defined in exact terms. This modelling procedure attempts to address this problem by using a 'representative product'. Comparing this idealised product with a real product may reveal significant differences. As a consequence a more detailed assessment at a later stage in the design process is a requirement.

UNCERTAINTY OF THE INPUTS The design requirements form the basis of the inputs to the models. As nothing is known with absolute certainty, the data has an associated uncertainty, which may be expressed as a form of distribution. The usual solution to this problem is to use single mean values.

At the early stage in the design process this is magnified, as the design requirements are not known to the accuracy required for a detailed life cycle assessment.

Reviewing the sources of error in modelling and taking into account the 'fuzzy' nature of the data at the early stages of design, the model's accuracy must not be overestimated. The models are at best a rough estimate of reality, but possibly better than an order-of-magnitude estimation. That is considered sufficient to assess the importance of the different life cycle stages, so as to focus the attention of the designer on that life cycle stage. But even a detailed life cycle assessment at a later stage of the design process requires such a magnitude of data, with a wide range of uncertainty, that the so determined waste stream quantities have an associated error which is significant.

[9]Integrating costing requires current cost data (e.g. material cost, energy cost, relative product cost or percentage of material cost as part of the product cost, etc., depending on the costing methods implemented).

3.10 Summary

The LCA-method described in this section is a method that focuses on usability to designers, while being able to represent the data required for LCA in a manner that enables an analyst to carry out a LCA. It is believed that the compromise struck here has the potential for assessing the life cycle of products at the early design stage.

The method integrates LCA into the design process by modelling the Life Cycle Inventory (LCI) of standard products and by relating the inventory of the various life cycle stages to Design Parameters (DPs) via, so called, Life Cycle Parameters (LCPs).

The novel approach of this thesis is that it was realised that there are a limited number of parameters that influence the major part of a life cycle. These parameters are called life cycle parameters and they include e.g. mass of the product (and its average relative material composition), efficiency and retirement strategies. The LCPs are correlated to the inventory of the different life cycle stages. Furthermore the LCPs are linked to DPs, i.e. for a given DP the analyst determines the extremes of the LCP. These extremes represent the best and worst case for a whole product range, and includes "what is currently possible", and "what is common". This highlights the LCP that has a large influence on the whole life cycle and this helps the designer to focus on optimising this LCP, to obtain an overall optimum life cycle impact.

The strength of this method is that it integrates LCA into the design process, by correlating DPs (i.e. what the designers know anyway) to the whole life cycle inventory, which can then be used to complete the LCA (i.e. environmental impact assessment and improvement phase). Utilising knowledge of the designer is seen as the important aspect of integration.

A short introduction of how costing methods may be incorporated in a life cycle assessment tool, illustrate the parallel consideration of costing within this method.

The sensitivity in modelling due to inherent model inaccuracies and input uncertainty must always be considered when modelling and when using and applying the models. Therefore the inventory of the concept design can only be seen as rough estimate of reality.

In order to clarify the points made in this chapter, to illustrate how the models are derived with real product data and to demonstrate the use of of the method in a design situation Chapter 4 presents modelling case studies and Chapter 5 presents an application of the models. The topics covered are:

SEALED LEAD ACID BATTERIES Section 4.2: demonstrates how historical and widely accepted empirical observations are used to determine simple models of LCP's as a function of DP's.

3-PHASE ASYNCHRONOUS MOTOR Section 4.3: demonstrates how theoretical observations are used to determine a basic format of the equations that link the LCP's to the DP's. This is slightly adapted to suit the actual data, therefore this represents a theoretical and empirical approach to obtaining the mathematical representation.

HYBRID VEHICLE: URBAN BUS Chapter 5: Illustrates how an approximate inventory is determined by applying the models developed in the previous chapter. The components modelled are the 'best case' models representing what is possible today.

A further application of this method on modelling the LCI of rolling element bearings, which are mechanical devices of low complexity, can be found in [Abd Elmaksoud 1999].

4 Case Studies of Generic Parts

4.1 Overview

This chapter is intended to show how the method, that is explained in Section 3.5 and Section 3.6, is applied.

The choice of the case studies was governed by the following considerations:

- the product is mass produced by a number of manufacturers and is widely used in engineering,
- the product functions according to a proven technology that has undergone significant technological evolution in the past,
- the product is available in a whole range of sizes depending on the application.

The following specific case studies are discussed in detail in this chapter:

1. Sealed Lead Acid Batteries, which are electrochemical devices of low complexity;
2. Three-Phase Induction Motors, which are electromechanical devices of medium complexity.

The case studies further highlight different aspects of the life cycle inventory modelling. While the battery mass model depends on satisfying two correlated design parameters (energy and power requirement) to determine the battery mass, the electric motor mass model depends on only one design parameter (torque). The electric motor efficiency model illustrates how two design parameters are required (torque and number of poles) to determine the efficiency.

The versatility of this modelling method is highlighted by these case studies and the method can be used for modelling LCP and the inventory of products from other industries, such as the electronics, information technology, building industry and even industries such as health care and other service providers. It is a matter of establishing the right DPs and LCPs and obtaining relevant data.

The case studies are structured as follows:

- Background information, i.e. introduction to the generic part, characteristics and application
- Working principle, including theoretical background with respect to the DPs
- Construction (internal construction, variants)
- Design and Life Cycle Parameters
  - Life Cycle Parameter models
  - Life Cycle Inventory models
  - Limits and applicability of the models
- Discussion and Conclusions

It must be stressed, that the case studies are mainly shown to demonstrate how the design and life cycle parameters are determined and how they are linked to the life cycle inventory. As part of this project it was not possible to carry out an exhaustive survey on the manufacturing inventory, by questioning all manufacturers of the case study products, but only few data with this respect could be accumulated. It is not part of this thesis to show a fully completed life cycle inventory of a product, but to show the method of how it is represented, to be useful at the concept stage of the design process. If there is the general willingness of industry to supply the relevant data, as it was experienced with some companies during this project, then the cost of extracting the data is low and is therefore *not* an inhibiting factor. This emphasises the practicality of this method to making life cycle concept design decisions.

Another part of the life cycle inventory that is neglected from a data point of view in this thesis is the post-use inventory. As with the previous point it was not possible to carry out a complete survey of relevant industries to find out what the recycling, remanufacturing, reuse and disposal rates are of the case study product and what the inventory is associated with these retirement routes. Again it is explained how the life cycle parameters are linked to the inventory of the post-use phase, with an emphasis on the practicality of the whole method.

4.2 Sealed Lead Acid (SLA) Batteries

4.2.1 Background Information

In the late 60's the sealed lead acid (SLA) battery was developed, which allowed the lead acid battery to be used where clean operating conditions are required.

There are many choices for rechargeable systems, but lead-acid batteries are still the most widely used as they are usually more economical and have a high tolerance for abuse. They are used as a starting, ignition and lighting (SLI) power source in internal combustion motor vehicles and provide motive power to a variety of products ranging from golf caddies to submarines. SLA batteries used as standby power supplies are especially useful to avoid having a dedicated battery room as no emissions exit the battery under normal operating conditions.

One constructional difference from conventional batteries is that the cells of SLA batteries are designed with a resealable pressure valve to keep the internal pressure within a specified range. On build-up of gasses (e.g. during charging and especially during overcharging, see Section below) the valve opens and releases the excess gasses, but closes thereafter to prevent oxygen from entering the cell.

The SLA cells are made in two designs:

1. cylindrical design with a spirally wound plate
2. prismatic design with flat plates

The venting characteristics are different for the two designs. The prismatic designs usually vent at lower pressures (4 to 100 kPa) compared to the cylindrical designs (200 to 400 kPa) [Linden 1995]. Prismatic designs are often called valve-regulated lead acid (VRLA) cells, while cylindrical cells are commonly referred to as SLA cells. In this context the distinction is not made. As both designs are 'sealed' they will be referred to as SLA cells.

In SLA batteries the electrolyte is immobilised according to one of the two following methods [Linden 1995]

ABSORBED ELECTROLYTE The electrolyte is absorbed in a highly porous and absorbent micro-fibreglass mat. The fibreglass mat is partially filled with the electrolyte of the required acid concentration.

GELLED ELECTROLYTE Silica is added to the electrolyte, causing it to harden into a gel.

This immobilisation of the electrolyte has an advantage in that the SLA battery can be operated in different orientations without spillage.

Lead acid batteries use as a major part toxic materials which are required for its function. The largest part is lead and due to its toxicity legislation has enforced an effective recycling scheme in most western countries. In the USA over 90% of the lead is recycled [Gaines & Singh 1995] and in Britain it is estimated that about 90% of the SLI batteries are recycled and more than 90% of motive and standby power batteries are recycled [Bush 2000].

4.2.2 Working Principle

A battery is an electrochemical device that stores chemical energy which can be released as electrical energy when the battery is connected to an external load. Under these conditions the chemical energy is converted into electrical energy and a current flows through the circuit from one electrode to the other.

The electrodes are pure lead grids which are pasted with a mixture of lead oxides; these lead oxides are converted to the active materials in the 'formation' process, which is the process when the cell is charged for the first time. At the positive electrode lead dioxide ($Pb\,0_2$) is converted to lead sulphate ($Pb\,S0_4$) and at the negative electrode sponge metallic lead (Pb) is also converted to lead sulphate. In the charged state the electrolyte is sulphuric acid which is converted to water in the discharged state. The cell reaction is shown in **Eq. (4.1)** to **Eq. (4.3)**.

$$\underbrace{Pb}_{\text{Negative Electrode}} + \underbrace{Pb\,O_2}_{\text{Positive Electrode}} + \underbrace{2\,H_2\,SO_4}_{\text{Electrolyte}} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} \underbrace{Pb\,SO_4}_{\text{Negative Electrode}} + \underbrace{Pb\,SO_4}_{\text{Positve Electrode}} + \underbrace{2\,H_2O}_{\text{Electrolyte}} \tag{4.1}$$

with the half cell reactions being

Negative Electrode: oxidation during discharge (Positive Terminal)

$$Pb + SO_4^{2-} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} \underbrace{Pb\,SO_4^{2-}}_{\text{in solution}} + 2\,e^- \tag{4.2}$$

Positive Electrode: reduction during discharge (Negative Terminal)

$$Pb\,O_2 + 4\,H^+ + 2\,e^- + SO_4^{2-} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} \underbrace{Pb\,SO_4^{2-}}_{\text{in solution}} + 2\,H_2O \tag{4.3}$$

During the discharge reaction the negative electrode has a potential of 0.356 V and the positive electrode has a potential of 1.685 V, resulting in an overall voltage of about 2.04 V per cell depending further on the acid solution. The discharge reaction also shows that the electrodes dissolves into the electrolyte during the discharge reaction. When charged — and especially when overcharging occurs — an electrolysis process will produce hydrogen (H_2) and oxygen (O_2) from the water. In sealed lead acid batteries a catalytic re-combiner produces water from the hydrogen and oxygen and so does not require a refilling of the electrolyte. A resealing safety vent is provided to handle pressure build-ups during abusive overcharging.

When recharging the lead-acid battery the lead-sulphate needs to be converted back to the active plate material. If the battery does not remain discharged for long or only remains slightly discharged then this is not problematic. On the other hand, if

the battery stays discharged for a relative long period or is subjected to repeated deep discharges without fully recharging between cycles the sulphate material can harden into crystals which are more difficult to convert. Until the sulphate is converted the sulphated parts of the plates are useless and eventually leads to the failure of the battery. This is the most common cause of failure.

The sealed lead acid battery design differs from the flooded type in such a way that it promotes the chemical recombination of oxygen at the negative electrode. This eliminates to a large extent the gassing (hydrogen and oxygen) associated with lead acid batteries as is illustrated in **Fig. 4.1**. This 'oxygen-recombination cycle' [Rand, Woods & Dell 1998] is shown in the following:

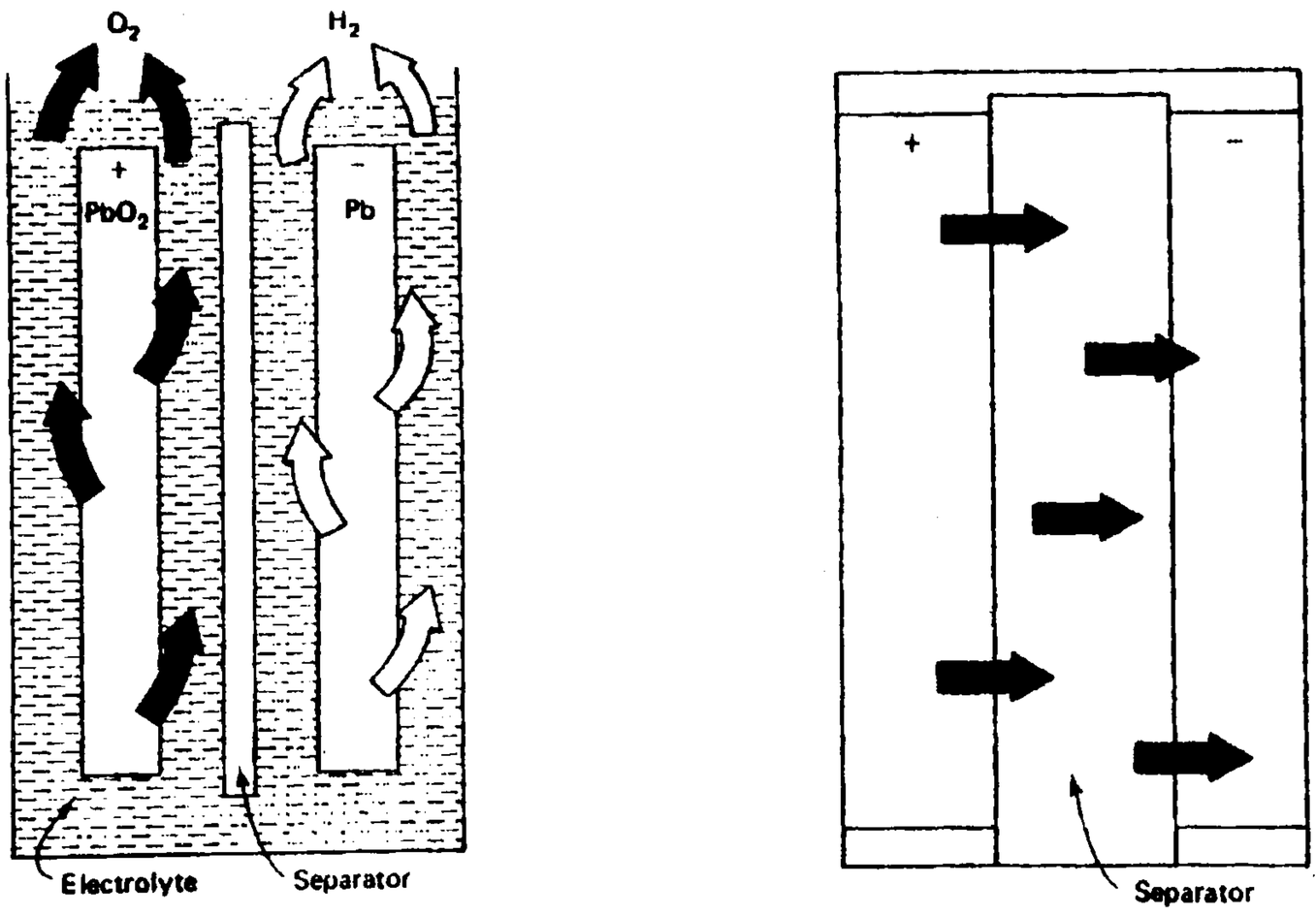
Positive Electrode:

$$H_2O \longrightarrow 2H^+ + \frac{1}{2} O_2 + 2e^- \tag{4.4}$$

Negative Electrode:

$$PB + \frac{1}{2} O_2 + H_2SO_4 \longrightarrow PBSO_4 + H_2O \tag{4.5}$$

$$PBSO_4 + 2\,H^+ + 2e^- \longrightarrow PB + H_2SO_4 \tag{4.6}$$



(a) (b)

Figure 4.1: Recombination technology in Lead-acid batteries. (a) conventional desing (flooded (b) recombination electrolyte design (sealed) [Crompton 1995]

4.2.2.1 Failure Modes

SLA Batteries fail mainly because [Berndt 1997, p. 456]

- Disintegration of the active material
- Re-crystallisation effects, sulphation
- Corrosion of positive grid and conducting elements
- Hydrogen evolution
- Evaporation of water vapour
- Corrosion of negative grid and conducting elements

4.2.2.2 Performance Parameters

The two main parameters that are used to measure the battery's performance are:

1. voltage
2. capacity

Voltage The voltage of batteries determined by the active materials used. The reduction and oxidation reactions are shown in **Eq. (4.1)** to **Eq. (4.3)** and it was mentioned that the sum of potential from both reactions is the voltage that a battery can produce. In case of lead-acid batteries this is about 2.04 V. This is the standard electrode potential. Factors such as the acid concentration of the battery affect the voltage and the typical open circuit voltage of a commercial lead-acid battery is 2.15 V. Cells are connected together in series so that their voltages are added thus meaning that lead acid batteries come with nominal voltages of 2 V, 4 V, 6 V etc.

Capacity It is essentially the number of electrons that can be obtained from the battery. Since current is the number of electrons per unit time, cell capacity is the current supplied by a cell over time and is measured in ampere hours (Ah). The capacity of a battery depends on the active material it contains. The capacity of a single cell can range from a fraction of Ah to thousands of Ah. An increase in capacity can be achieved by using larger cells or by connecting batteries in a parallel configuration

4.2.2.3 Peukert's Observation

It is a well known fact that the energy a battery can supply is dependent on the power taken out of the battery. This was first shown by Peukert in 1897, where he proposed the empirical relationship between the capacity and the current drawn as follows [Peukert 1897]:

$$I^n \, t = \text{constant} \tag{4.7}$$

where I is the current drawn from the battery, t is the time over which the current is required and n is a constant characteristic for a given battery. The closer the constant is to unity, the more efficient is the utilisation of the active material for large discharge currents. For SLA batteries typical values of n range from 1.1 to 1.3.

Assuming that C_1 is the capacity, resulting from drawing a current I_1 over the time t_1, and C is the capacity, resulting from drawing a current I over the time t, and with $C = I \, t$ the relationship between current and capacity is

$$C = C_1 \left(\frac{I_1}{I}\right)^{n-1} \tag{4.8}$$

Peukert's equation does not work well for 'large' currents I, as it significantly overpredicts the capacity C. This is shown in **Fig. 4.2 (a)**.

Using Peukert's Equation to Determine Relationship between Specific Energy and Specific Power From **Eq. (4.7)** we get $t = K/I^n$ where K is the constant. Furthermore Energy E is equal to Power P times the time the power is supplied t, i.e. $E = P \, t$. With power being equal to the product of voltage and current (i.e. $P = V \, I$) and neglecting the voltage drop during discharge, Energy E is

$$E(P) = V^n \, K \, P^{1-n} \tag{4.9}$$

The specific energy e is energy per unit mass, i.e. $e = E/m$, and analogous specific power p is $p = P/m$. By dividing both sides of **Eq. (4.9)** by mass m it can be shown that the relationship between specific energy and specific power is

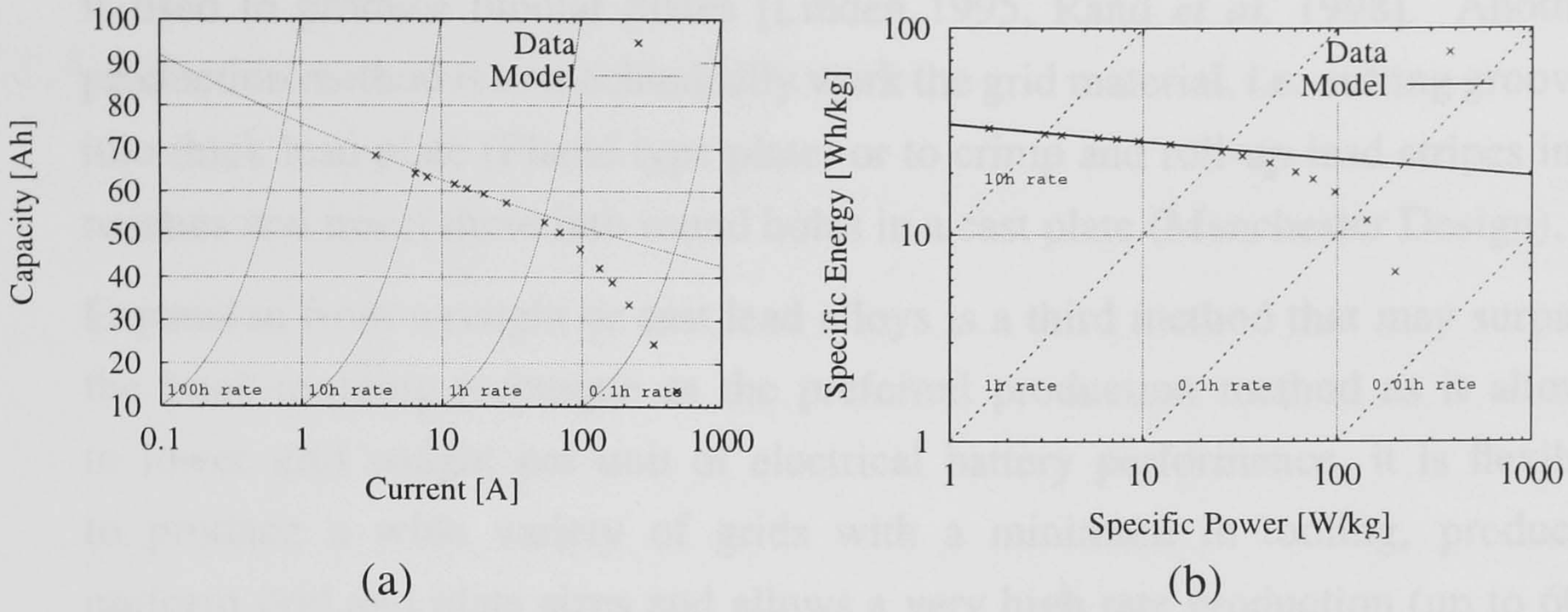
$$e(p) = \frac{1}{\left(\frac{m}{V}\right)^n \; K^{-1} \; p^{n-1}} \tag{4.10}$$

With m, V, n and K being constant for a given battery **Eq. (4.10)** may be rewritten as

$$e(p) = \frac{1}{b \; p^c} \tag{4.11}$$

with $c = n - 1$ and $b = \left(\frac{m}{V}\right)^n \; K^{-1}$.

In **Fig. 4.2 (b)** it is shown how **Eq. (4.11)** substantially over predicts the specific energy for large specific powers. This is not unique to this specific battery, but can be shown to be true for all lead acid batteries [Rand *et al.* 1998].



(a) (b)

Figure 4.2: Models based on Peukert's equation and Data (Hawker 65 Ah SLA battery [Haw 1998]). (a) Capacity vs. Current (Model according to **Eq. (4.8)** with $n = 1.083$ and $C_1 I_1^{n-1} = 272960$) (b) Specific energy vs. specific power (Model (in SI-units) according to **Eq. (4.11)** with b=8.0767×10^{-6} and c=0.083)

4.2.3 Construction of SLA Batteries

The SLA battery assembly comprises of the following components:

PLATE GRID supports the frame for the active material of the positive and negative electrodes, must conduct electricity and must withstand the acid over the entire life of the battery. It is therefore mostly made of an alloy of lead, as this is the most cost effective choice.

Lead-calcium (ca. 0.08% Ca) alloys or pure lead grids are mostly used in SLA batteries as this reduces the gassing during charging by a factor of 5 compared to lead-antimony alloys (4-6% Antimony), which were used in standard lead-acid batteries [Crompton 1995]. Modern battery grids fall into three classes [Linden 1995]:

- Low antimony alloy (Sb: <4% antimony) lead-acid batteries require the addition of small amounts of other elements to prevent grid fabrication defects and grid brittleness, e.g. sulphur, arsenic and selenium act as grain refiners to decrease the lead grain size.
- calcium (Ca: 0.03-0.2%) alloy with a possible addition of tin (Sn: 0.25-2%) or aluminium to add stiffening properties to the grid.

- lead-tin alloy (Sn: 0.01-1.5%).

The grids are mostly produced by casting methods of which the book-mold casting accounts for the largest proportion for plate grids, while pressure-casting is used to produce tubular plates [Linden 1995, Rand *et al.* 1998]. Another production method is to mechanically work the grid material, i.e. cutting grooves into thick lead plate (Planté type plate) or to crimp and roll-up lead stripes into rosettes and insert these into round holes in a cast plate (Manchester Design).

Expansion from wrought or cast lead alloys is a third method that may surpass the book-molding technique as the preferred production method as it allows to lower grid weight per unit of electrical battery performance, it is flexible to produce a wide variety of grids with a minimum in tooling, produces uniform grid and plate sizes and allows a very high rate production (up to 600 plates/minute). Here, thin strips of lead alloy are produced by a variety of appropriate metal-working processes and then it is cut to the width specified by the battery manufacturer. The grid is formed by subsequently expanding the wrought strip.

NEGATIVE AND POSITIVE PLATES are made by pasting a mixture of lead oxide, sulphuric acid and water onto the plate grid which is subsequently converted to the active materials in the formation process. The negative plates include expanders to prevent the negative plate material from reverting to a dense, inactive mass due to contraction.

So-called 'cranking' batteries are used where the high energy bursts are required for a high load application. A large number of thin plates maximises the plate area that can be exposed to the electrolyte. But thin plates are more easily destroyed by deep discharge and therefore deep discharge should be avoided in thin plated lead acid batteries. On the other hand 'deep-cycle' batteries have thicker plates to withstand the repeated deep discharge.

SEPARATOR SHEETS are made of electrically insulating, porous material which are used as spacers between the plates to prevent short circuits within the cell. The material used is latex impregnated glass fibre, resin impregnated cellulose fibre, sintered PVC, silica/polyethylene or silica rubber.

CONTAINER is the the outside shell of the battery. It is usually a one-piece rectangular container moulded from polypropylene, acrylonitrile-butadiene-styrene (ABS) resin, hard rubber or other plastic-like materials.

ELECTROLYTE is a dilute solution of between 28% and 42% sulphuric acid (H_2SO_4) and 58% to 72% of distilled water (H_2O). In some SLA batteries the electrolyte is immobilised in a thixotropic silicic acid.

4.2.4 Design and Life Cycle Parameters

It was mentioned that the main performance parameters of batteries are voltage and current capacity. This leads to common DPs Power (= Voltage × Current) and Energy (= Power × Time). These two DPs are not independent for a given battery, which means that the energy, that a battery can supply, depends on how much power is taken out (see Section 4.2.2.3). This poses a problem as it adds another degree of complexity to the modelling procedure. The relationship between power and energy is often displayed in relative terms and plotted as graphs of mass specific power [W/kg] versus mass specific energy [Wh/kg]. These are sometimes called *Ragone Plots*. As can be seen the relative representation of the two parameters includes the LCP mass. This is convenient as only one model is required to capture the relationship between the energy density and the power density. Once the point on that relationship is found, the LCP mass can be determined by determining whether the DP power or the DP energy leads to larger mass.

Therefore the most important design parameters that are used when choosing a battery are

- Short term (maximum) required power [W]
- Long term required power [W]
- Time over which the power is required (capacity)
- Expected life
- Mass and/or volume of battery, especially if product is moving (e.g. hybrid electric vehicle)

The life cycle parameters are the

- mass and specific material composition of a SLA battery
- efficiency of charging and discharging cycles
- expected life
- other use related matters (e.g. maintenance, evaporation or spillage of electrolyte)

- recyclability and actual recycling rates

The capacity of a lead-acid battery changes with the output current that is required, which means that a large supply of power in a short time will yield a smaller capacity than a low supply of power in a proportionally longer time (see **Fig. 4.2**). Though the reserve capacity left after a short burst is larger compared to the long term discharge. The total long term capacity is the ultimate capacity limit of the battery. But the size of the battery will be dictated by either the short term power burst or the long term power requirements, depending on the application.

A common way of displaying the characteristics of battery technology is in the form of mass specific power [W/kg] and mass specific energy [Wh/kg]. As mentioned in the previous paragraph the power and energy are related; determining the relationship between the mass specific power and the mass specific energy can be used to relate the DP's power and energy to the LCP mass. A designer will choose a battery according to what power is required over the specified time. If an application requires different powers over different times the maximum mass from all modes (due to either the power requirement or the energy requirement at a specific mode) will determine the minimum mass of required batteries.

It is also noteworthy that battery-industry standards have contributed to the fact that batteries (of the same type, composition, and size) from different manufacturers are interchangeable.

4.2.5 Modelling the Life Cycle Parameters

4.2.5.1 Mass

Extending Peukert's Equation to Determine a Relationship between Specific Energy and Specific Power As was shown in Section 4.2.2.3 (p. 105), Peukert's Equation does not lead to a satisfactory model for representing the mass specific energy as a function of mass specific power. It was found that by adding the constant, a, to **Eq. (4.11)**, such that

$$e(p) = \frac{1}{a + b\,p^c} \tag{4.12}$$

then the model captures the behaviour for the full range of specific power. Here e is the specific energy, p is the specific power and a, b and c are constants. Examples of the models are shown in **Fig. 4.5** (p. 112).

The model from **Eq. (4.12)** is used to model

- the best case [Ragone 1995, Hively 2000]
- the Hawker Genesis Range [Haw 1998]

Upper Limit Generic Product Range Model (ULGPRM) representing the best case from all SLA batteries. There are many lead acid batteries in use today. For the analysis of the relationship between the specific energy and the specific power, data from 229 batteries making up 12 product ranges from 7 manufacturers where analysed. This is shown in **Tab. 4.1**. All the 1666 data points are plotted in **Fig. 4.4**.

Table 4.1: List of batteries

Manufacturer	No. of Ranges	No. of Batteries
C&D Technologies[a]	3	137
Electrosource	1	1
Hawker	2	10
Oerlikon	1	8
Optima	1	1
Power-Sonic	1	6
Yuasa[b]	4	66
total	13	229

[a]The data is not sufficient for individual battery models.
[b]Some flooded standby batteries are included

The summarised data from a previous study is used to determine the ULGPRM [Ragone 1995]. The data points in **Fig. 4.4** that lie just below the 'best line' (ULGPRM) represent batteries that may be used for hybrid electric vehicles. The line is taken from **Fig. 4.3** representing the high power and/or bipolar lead acid batteries. It represents the most advanced lead acid battery in terms of delivering the highest power and energy for the least mass.

In **Fig. 4.4** it can be seen that many points lie at some distance from the best possible line. This means that these batteries require a larger mass, and therefore a larger pre-use inventory, to achieve the same performance compared to batteries lying nearer to the best possible line.

The large number of points clustered in the lower left corner of **Fig. 4.4** are flooded lead acid batteries (Yuasa) used for uninterrupted power supply in the telecommunications industry and other industries. It illustrates the wide variety of lead acid batteries available.

The equation for the best line follows the same format as **Eq. (4.12)** with the coefficients as shown in **Tab. 4.2**. The best line is also shown in subsequent plots as a this dotted line as a reference line.

Specific Product Models (SPMs, Hawker Genesis, [Haw 1998]). The coefficients for **Eq. (4.12)** with respect to the Hawker Genesis range are listed in **Tab. 4.3**.

A graphical representation of the models and data is given in **Fig. 4.5**.

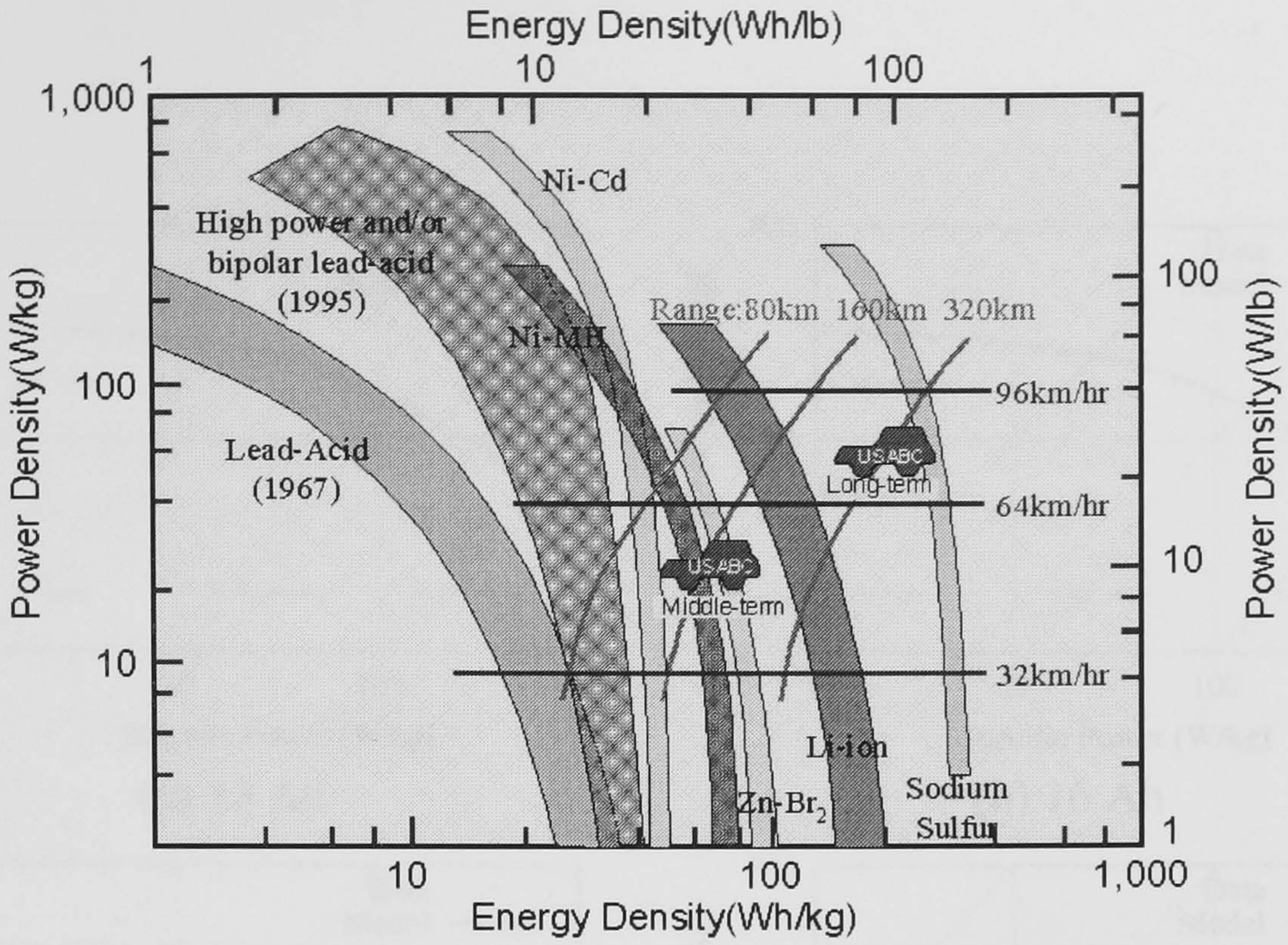


Figure 4.3: Ragone Plot (specific power vs. specific energy) for different types of batteries [Ragone 1995]

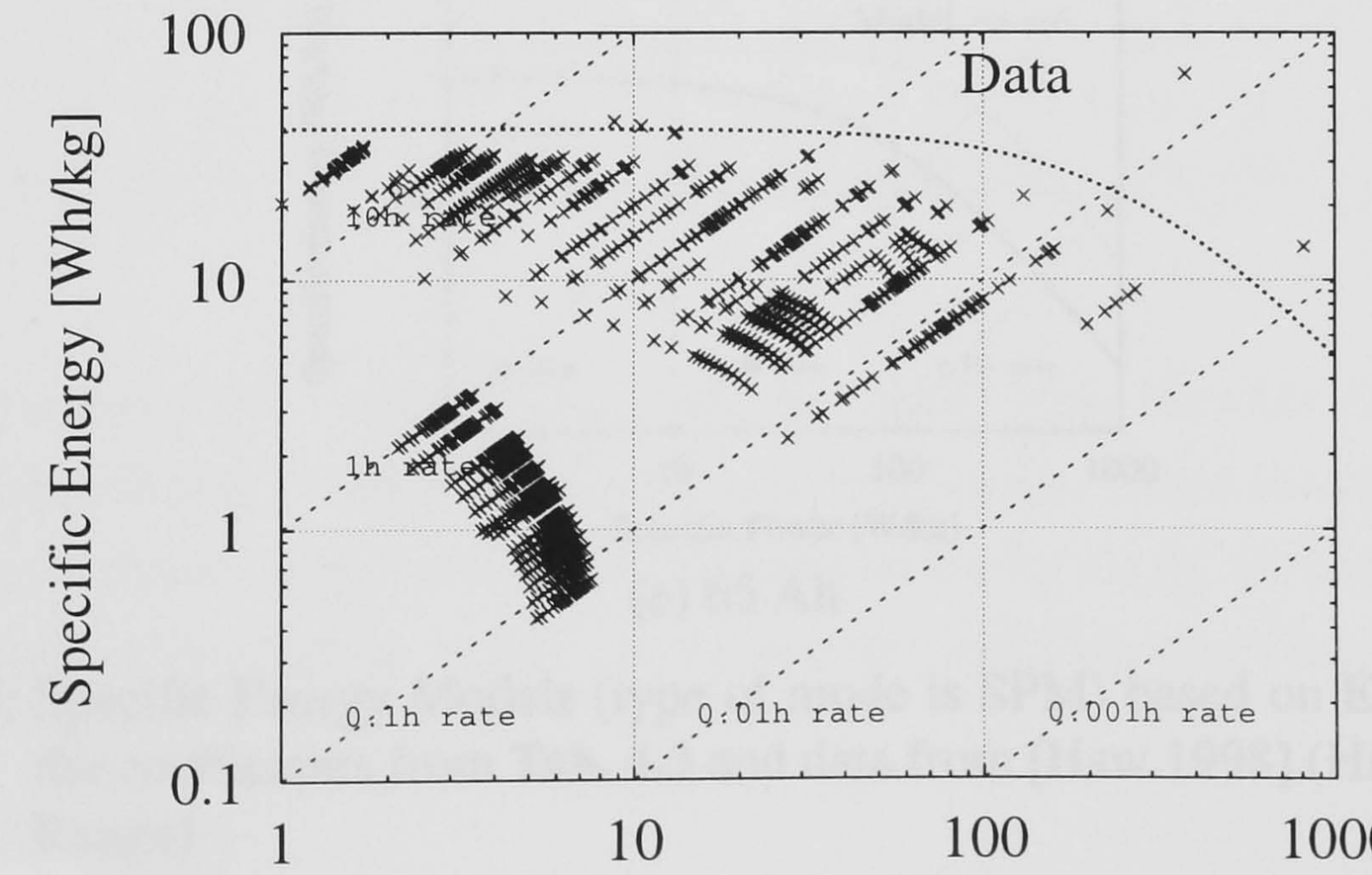
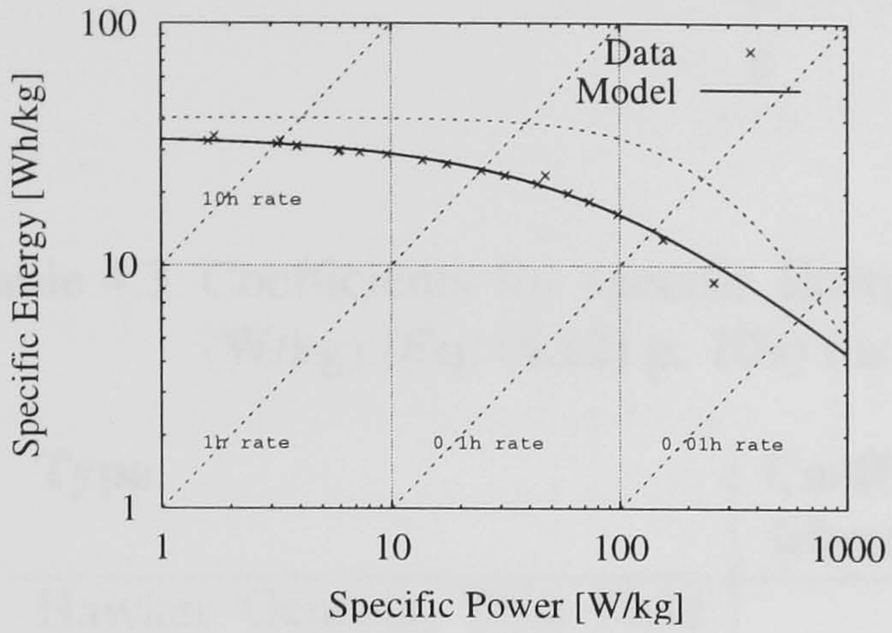
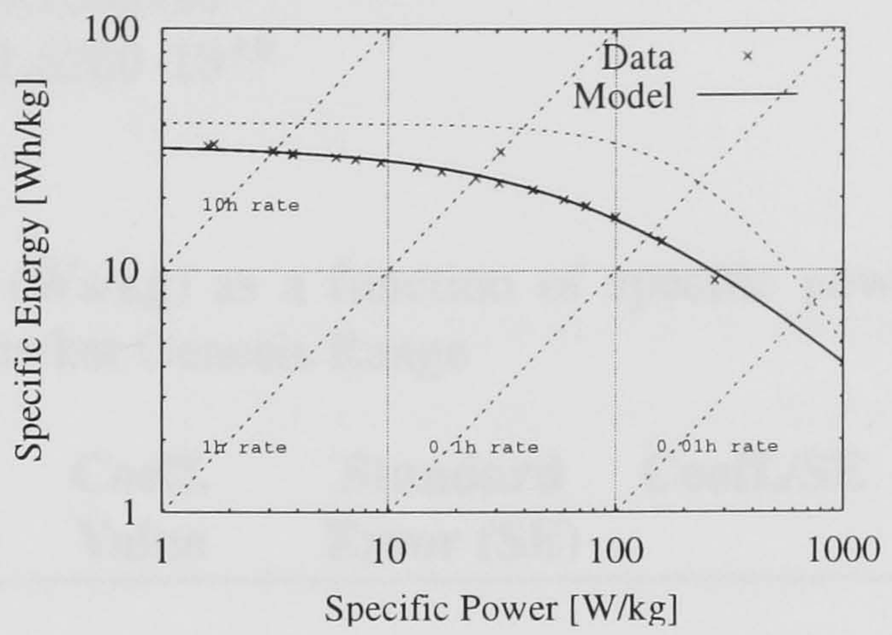


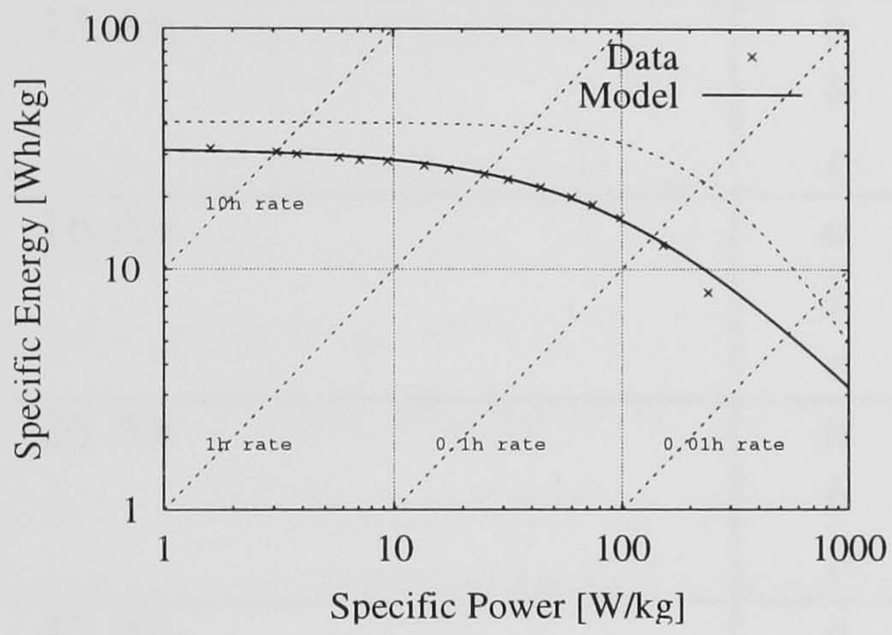
Figure 4.4: Specific energy vs. specific power Data plotted for all the collected data including the practical limits for hybrid vehicles



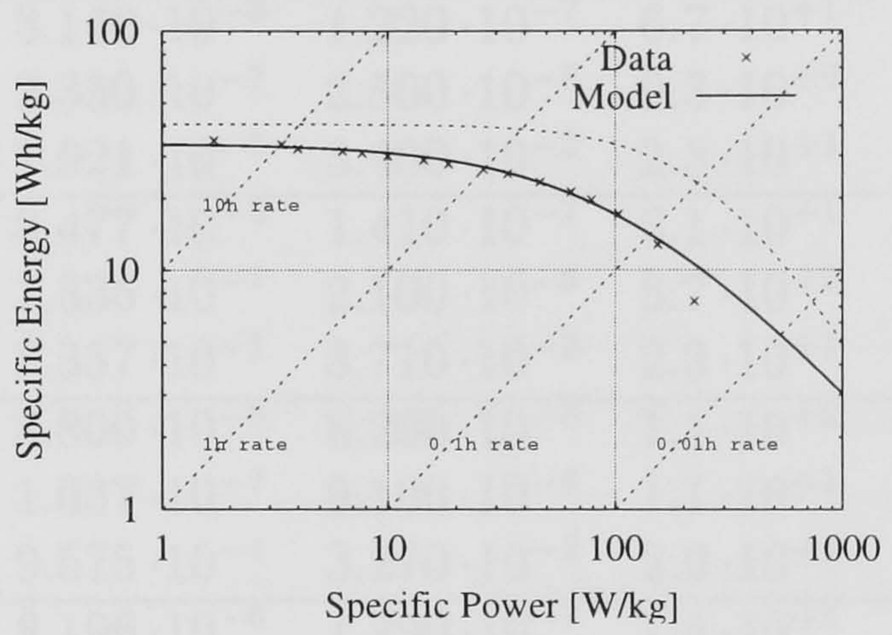
(a) 13 Ah



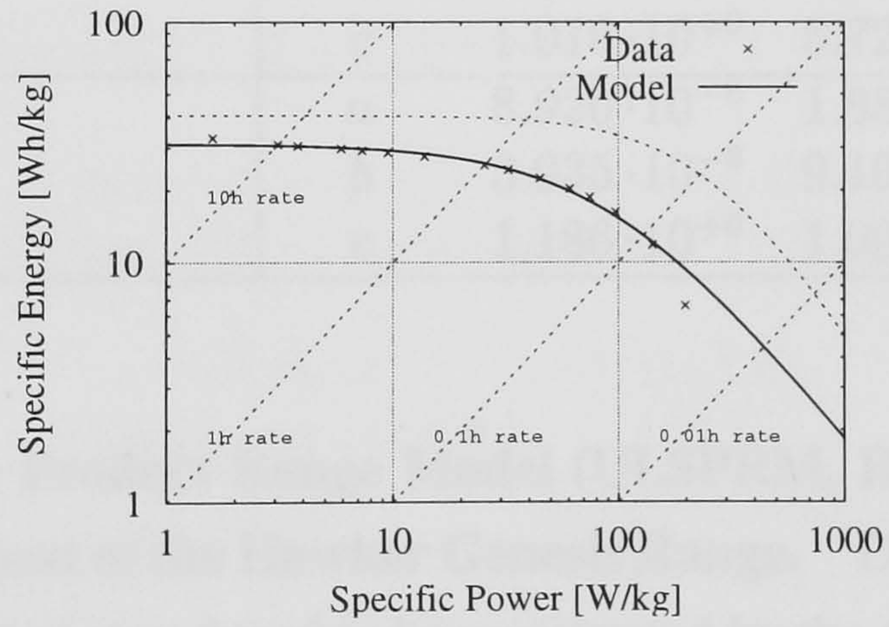
(b) 16 Ah



(c) 26 Ah



(d) 42 Ah



(e) 65 Ah

Figure 4.5: Specific Energy Models (type of mode is SPM) based on **Eq. (4.12)** with the coefficients from **Tab. 4.3** and data from [Haw 1998] (Hawker Genesis Range)

Table 4.2: Coefficients for best possible specific energy (Ws/kg) as a function of specific power (W/kg) of SLA batteries for **Eq. (4.12)** p. 109 (ULGPRM).

Coefficient	**Value**
a	$0.6795 \cdot 10^{-5}$
b	$0.1300 \cdot 10^{-8}$
c	$1.5260 \cdot 10^{+0}$

Table 4.3: Coefficients for specific Energy (Ws/kg) as a function of specific power (W/kg) (**Eq. (4.12)** p. 109) for Hawker Genesis Range

Type	**Coeff-icient**	**Coeff. Value**	**Standard Error (SE)**	**Coeff./SE**
Hawker Genesis, Thin Plate Technology, AGM				
13 Ah	a	$8.140 \cdot 10^{-6}$	$1.220 \cdot 10^{-7}$	$6.7 \cdot 10^{+1}$
	b	$2.330 \cdot 10^{-7}$	$2.500 \cdot 10^{-8}$	$9.3 \cdot 10^{+0}$
	c	$7.921 \cdot 10^{-1}$	$3.400 \cdot 10^{-2}$	$2.3 \cdot 10^{+1}$
16 Ah	a	$8.477 \cdot 10^{-6}$	$1.410 \cdot 10^{-7}$	$6.1 \cdot 10^{+1}$
	b	$1.836 \cdot 10^{-7}$	$2.100 \cdot 10^{-8}$	$8.7 \cdot 10^{+0}$
	c	$8.357 \cdot 10^{-1}$	$3.710 \cdot 10^{-2}$	$2.3 \cdot 10^{+1}$
26 Ah	a	$8.800 \cdot 10^{-6}$	$8.200 \cdot 10^{-8}$	$1.1 \cdot 10^{+2}$
	b	$1.037 \cdot 10^{-7}$	$9.100 \cdot 10^{-9}$	$1.1 \cdot 10^{+1}$
	c	$9.575 \cdot 10^{-1}$	$3.270 \cdot 10^{-2}$	$2.9 \cdot 10^{+1}$
42 Ah	a	$8.196 \cdot 10^{-6}$	$1.290 \cdot 10^{-7}$	$7.4 \cdot 10^{+1}$
	b	$7.459 \cdot 10^{-8}$	$1.100 \cdot 10^{-8}$	$6.8 \cdot 10^{+0}$
	c	$1.016 \cdot 10^{+0}$	$5.720 \cdot 10^{-2}$	$1.8 \cdot 10^{+1}$
65 Ah	a	$8.920 \cdot 10^{-6}$	$1.880 \cdot 10^{-7}$	$4.7 \cdot 10^{+1}$
	b	$3.935 \cdot 10^{-8}$	$9.100 \cdot 10^{-9}$	$4.3 \cdot 10^{+0}$
	c	$1.186 \cdot 10^{+0}$	$1.000 \cdot 10^{-1}$	$1.2 \cdot 10^{+1}$

Upper Limit Specific Product Range Model (ULSPRM, Hawker Genesis, [Haw 1998]), representing best of the Hawker Genesis Range. Data for the ULSPRM of the Hawker Genesis range was found to be represented by the 42 Ah battery, since this battery consistently achieves higher values than any other Hawker Genesis battery.

4.2.5.2 Efficiency

The capacity efficiency, η_{Ah}, and energy efficiency, η_{Wh}, of the charging process is defined as follows:

$$\eta_{\text{Ah}} = \frac{\text{Available Capacity [Ah]}}{\text{Required Charge Input[Ah]}} \tag{4.13}$$

$$\eta_{\text{Wh}} = \frac{\text{Available Energy [Wh]}}{\text{Required Charging Energy [Wh]}} \tag{4.14}$$

The energy efficiency is always lower than capacity efficiency because of the voltage drop between charging and discharging. The efficiencies are shown in **Tab. 4.4**.

Table 4.4: Charging Efficiency of Sealed Lead Acid Batteries [Berndt 1997]

Capacity Efficiency	**Energy Efficiency**
η_{Ah}	η_{Wh}
0.8 - 0.94	0.65 - 0.8

The efficiency is only valid for charging processes restricted by time and overcharging will lead to the efficiencies to tend towards zero. The highest efficiency can be achieved for a partial recharge after a rapid discharge. Also, the higher the state of charge, the lower the charge acceptance is and therefore the lower the efficiencies tend to be.

4.2.5.3 Expected Life

Batteries have a limited life which ends when the capacity of the battery falls below an acceptable value (between 80% and 60% of the initial capacity, depending on the application [Berndt 1997]). In case the batteries are used as standby devices, which are rarely discharged, the expected life is quoted in calender time and in the case where the battery undergoes frequent cycles then the expected is quoted in how many cycles the battery can undergo before it degrades and the capacity falls below the acceptable value.

In **Tab. 4.5** typical values for advanced lead acid batteries are listed.

Table 4.5: Cycle life vs. depth of discharge data for the Hawker Genesis, the Hawker Cyclon and Optima 'Blue Top' series [Haw 1998, Haw 1999, Hively 2000]

Depth of Discharge (DoD)	**Cycle Life (CL)**
<10%[a]	9000 - 12000
10%	3000 - 4500
30%	1200 - 2500
50%	800 - 1250
80%	400 - 600
100%	300 - 400

[a] At very high discharge rates

Using the values from **Tab. 4.5** it was found that an equation correlating the cycle life, CL in number of recharging-discharging cycles, to the depth of discharge, DoD lies between 0 and 1, takes the form

$$CL = DoD^b \, e^{a+c \, DoD} \tag{4.15}$$

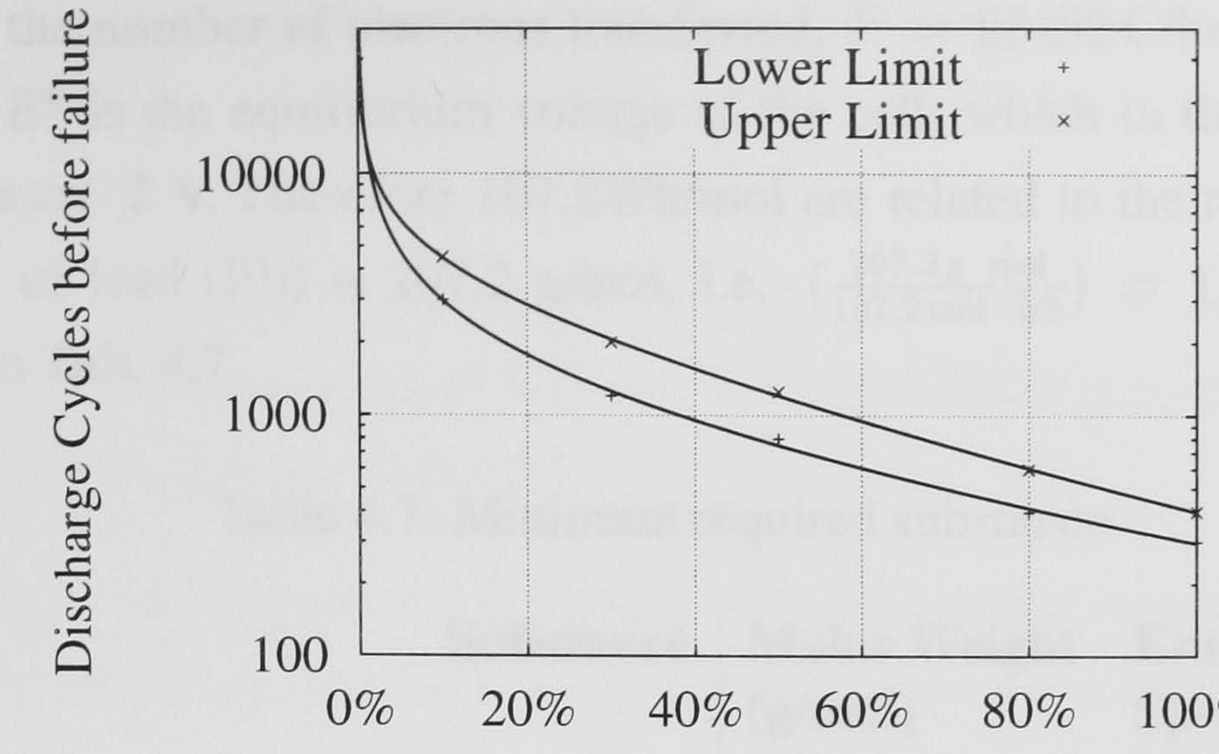


Figure 4.6: Cycle life plotted against depth of discharge for SLA batteries

where a, b and c are constants. For Sealed Lead Acid batteries the coefficients take the values shown in **Tab. 4.6**. In **Fig. 4.6** the data points and the models are represented in a graphical form.

Table 4.6: Coefficients for best possible Cycle Life (CL) as a function of Depth of Discharge (DoD) [$0 \leq DoD \leq 1$] of SLA batteries for **Eq. (4.15)**.

	Coefficient	Value
Upper Limit	a	7.6374
	b	-0.4053
	c	-1.6468
Lower Limit	a	6.7257
	b	-0.5978
	c	-1.0341

4.2.6 Modelling the Life Cycle Inventory

4.2.6.1 Relative Material Composition

Theoretical Considerations As was shown in Section 4.2.2 and Section 4.2.3 a lead-acid battery consists of various materials which are required to maintain the electro-chemical reaction. When the reactants on the left-hand side of **Eq. (4.1)** (p. 102) react to result in the right hand-side then 2 electrons migrate from the negative pole to the positive pole (see **Eq. (4.2)** and **Eq. (4.3)**). This means that amount of energy that can be converted to electrical energy, ΔG, is

$$\Delta G = -n\,F\,E^0 = -385,940\,\text{Ws/mol} = -107.2\text{Wh/mol} \tag{4.16}$$

with n being the number of electrons transferred, $F = 96485\,\text{C/kmol}$ is the Faraday constant and E^0 is the equilibrium voltage of the cell; which in the case of the lead acid battery is ca. 2 V. Therefore 107.2Wh/mol are related to the reactants. E.g. the molar weight of lead (Pb) is 207.2 g/mol, i.e. $(\frac{207.2\,\text{g mol}}{107.2\,\text{mol Wh}}) = 1.94\,\text{g/Wh}$. This is summarised in **Tab. 4.7**.

Table 4.7: Minimum required substance

	Substance	**Molar Weight [g/mol]**	**Energy Specific Mass [kg/kWh]**
Left Side of **Eq. (4.1)** (charged)	Pb	207.2	1.94
	PbO_2	239.2	2.23
	$2\,H_2SO_4$	2× 98.08	1.83
	Total		6.00
Right Side of **Eq. (4.1)** (discharged)	$2\,PbSO_2$	2× 303.30	5.66
	$2\,H_2O$	2× 18.02	0.34
	Total		6.00

The three main constituents Pb, PbO_2 and H_2SO_4 take up 32%, 37% and 31% respectively in the fully charged state. The theoretical minimum is $6\,\text{kg/kWh} = 1/(167\,\text{Wh/kg})$ for which mass a lead acid battery can deliver its energy.

Practical Considerations No lead acid battery functions however with those materials alone as is outlined in the following.

The 6 kg/kWh is increased by the following factors [Berndt 1997]:

- an acid dilution to about 28% to 42% results in the addition of between 2.5 kg/kWh and 4.7 kg/kWh of water. The acid requires to be diluted to not cause deterioration of the parts, especially the separator, but it must be still high enough to fulfil electrochemical requirements, such as good ionic conductivity.

- excess electrolyte (of the order of 10% to 30%) adds another 0.4 kg/kWh to 1.3 kg/kWh of the diluted sulphuric acid (typical is 20% excess acid solution, i.e. ca. 0.9 kg/kWh to 1.3 kg/kWh depending on the dilution). This is required to prevent the pure water forming at the state of discharge as this would cause unwanted chemical reactions and recharging would not be possible because of the lack of conductivity.

- increase due to active material utilisation, which is worse for deep discharge batteries due to the insulating effect of lead sulphate which coats the electrodes and thus inhibits further discharge

- at the positive electrode of between 23% and 50% material utilisation, requires an addition of between 2.23 kg/kWh and 7.47 kg/kWh of lead dioxide. (see **Tab. 4.8** and **Tab. 4.9**)
- at the negative electrode of between 36% and 71% material utilisation, requires an addition of between 0.79 kg/kWh and 3.46 kg/kWh of lead. (see **Tab. 4.8** and **Tab. 4.9**)

- an addition of between 5.0 kg/kWh and 20.0 kg/kWh is added for the grids internal connections, terminal ports, separators and cell casing

Table 4.8: Realistic utilisation figures and required substance

Battery Type	**Utilisation Figures for Positive Electrode (PbO_2)**		**Utilisation Figures for Negative Electrode (Pb)**	
	Actual Best [Berndt 1997] [Ah/kg]	**Percentage Utilisation of Active Material [%]**	**Actual Best [Berndt 1997] [Ah/kg]**	**Percentage Utilisation of Active Material [%]**
SLI (Car battery) (20h rate)	100-130	40-50	130-160	58-71
Submarine (10h rate)	100-110	40-43	110-130	49-58
Traction (5h rate)	60-90	23-26	80-100	36-45
Stationary (conventional)	60-100	23-39	80-100	36-45
Stationary (SLA)	66-90	26-35	80-140	36-63

Adding the additional mass associated with a real working lead acid battery means that the energy specific mass lies between 18 kg/kWh and 43 kg/kWh for a low discharge rate depending on the construction of the battery.

This range is relatively wide and is therefore of little use. Taking data from various battery manufacturers the range can be narrowed down considerably, by considering the application the battery is intended for and the construction principles.

Real Batteries The data in this section are mainly based on literature sources which have analysed the material content of specific batteries in the past and on manufacturers data supplied either directly or gathered from Material Safety Data Sheets (MSDS).

Table 4.9: Added electrode materiel due to material utilisation as shown in **Tab. 4.8**

Battery Type	**Positive Electrode PbO_2 [kg/kWh]** (2.23 +)	**Negative Electrode Pb [kg/kWh]** (1.94 +)
SLI (Car battery) (20h rate)	2.23-3.35	0.79-1.40
Submarine (10h rate)	2.96-3.35	1.40-2.01
Traction (5h rate)	6.35-7.47	2.36-3.46
Stationary (conventional)	3.49-7.47	2.36-3.46
Stationary (SLA)	4.14-6.35	1.13-3.46

Table 4.10: Mass Specific Energy and Energy Specific Mass for whole battery

Battery Type	**Mass Specific Energy [Berndt 1997] [Wh/kg]**	**Energy Specific Mass [kg/kWh]**
SLI (Car battery) (20h rate)	30-45	22-33
Submarine (10h rate)	35-55	18-29
Traction (5h rate)	25-32	31-40
Stationary (conventional)	20-28	36-50
Stationary (SLA)	20-31	32-50

Data from Material Safety Data Sheets (MSDS) The Material Safety Data Sheets (MSDS) are useful, as they are required to be supplied by all the manufacturers of products that include hazardous materials. They do not only actually list the materials but also specify the mass percentage of the constituents. The ranges are mostly given for the whole product range. This may lead to ranges being specified, but in the context of this work this is not disadvantageous as the whole product range is being analysed. In **Tab. 4.11** data from MSDS of various battery manufacturers is listed.

Table 4.11: MSDS Inventory data

Manufacturer	Product Name	Revision Date	Percentage of Total Weight [%]			
			Pb	PbO_2	H_2SO_4	Other Materials
Hawker	Cyclon	28/08/95	56-67		6-8	water 9-12 non-hazardous materials 17-25
Hawker	Genesis	05/09/97	68-71		6-7	water 9-11 non-hazardous materials 14-15
Power-Sonic	PS	31/10/98	70		8	water 12 Polystyrene 5 Fibre glass 5
Optima	800U, 800s	13/08/96	32-42	31-39	7-10	water 10-15 Polystyrene 2-6 Fibre glass 1-4
Johnson Controls	Sealed Gel Cell	01/04/98	50	21	9	water 13 lead sulphate <1 non. haz. mat. 6
Johnson Controls	Absorbed Glass Matt	01/04/98	50	21	9	water 13 lead sulphate <1 non. haz. mat. 6
Johnson Controls	Wet Flooded	01/04/98	34	31	12	water 22 lead sulphate <1

As can be seen in **Tab. 4.11**, in the case of Hawker and Power-Sonic the data for lead (Pb) and lead dioxide (PbO_2) is summarised. All batteries are sealed lead acid batteries, except for the last entry which is a conventional flooded battery.

A similar picture is given by battery inventories reported in literature. This is summarised in **Tab. 4.12**. It may be noted that the last two entries in **Tab. 4.12** represent the inventory of wet-cell designs from 1971.

Inventory Examples Assuming the best traction batteries, using the constants shown in **Tab. 4.2** for **Eq. (4.11)**, the energy specific mass for the 5h rate is 24.6 kg/kWh.

A second battery example is taken from the Hawker series (42 Ah) and using the constants in **Tab. 4.3** leads to 31.3 kg/kWh at a 5h discharge rate.

Taking this information and information from the previous section into account a generic lead acid battery suitable for traction comprises of the materials as listed in **Tab. 4.13**.

It is further noteworthy that about 52% of the lead used is recycled lead (1995 level) and this will increase to between 59% and 63% by 2005. The lead consumption for

Table 4.12: Inventory data from Literature

Source	Battery Type	Percentage of Total Weight [%]			
		Pb	PbO_2	H_2SO_4	Other Materials
[Rand *et al.* 1998]	SLA, 45 Wh/kg at $C_5/5$ rate	44	20	10	water 18 non-hazardous materials 8
[Lipman 1999]	SLA, 44 Wh/kg	44	27	10	water 15 non-hazardous materials 4
[Gaines & Singh 1995]	SLA, AGM, 45 Wh/kg	69		8	water 14 Polypropylene 6 Glass Fibre 2 non-hazardous materials 1
J. Power Sources [Anonymous 1977/78]	Wet Cell, Flat Plate, Traction	52	21	7	water 11 non-hazardous materials 8
J. Power Sources [Anonymous 1977/78]	Wet Cell, SLI	43	19	11	water 17 non-hazardous materials 10

batteries is also to increase from 66% to 73% over the same period [Pugh & Breeze 1995].

4.2.6.2 Manufacturing Inventory

As was explained in Section 3.6.1 an investigation into the manufacturing of each of the battery models from each of the manufacturers is not practical and also not required, since at the concept stage this level of detail would be overwhelming the design process.

Several battery manufacturers where contacted and asked to supply relevant manufacturing data. Only one company was able to supply the data in the time available. The data listed in **Tab. 4.14** was reported by [Murphy 2000].

Information on the in-house waste, recovery and recycling rates was not supplied due to time constraints. In cases where the in-house recovery and recycling rates are not known, they could be estimated from averages of the particular industry or a related industry.

Table 4.13: Estimated materials inventory of a SLA Battery with 40 Wh/kg (25 kg/kWh) and a 32 Wh/kg (31 kg/kWh) rating (over a 5 h discharge time).

Material	**Part**	**40 Wh/kg Battery**		**32 Wh/kg Battery**	
		Energy Specific Mass [kg/kWh]	**Percentage of Total Weight [%]**	**Energy Specific Mass [kg/kWh]**	**Percentage of Total Weight [%]**
Lead	Anode	4.9	20	7.0	22
	Grid	3.7	15	5.3	17
Lead Dioxide	Cathode	8.6	35	9.0	29
Sulphuric Acid	Electrolyte	2.0	8	2.2	7
Water	Electrolyte	2.9	12	3.1	10
Polypropylene	Casing	1.5	6	1.6	5
Glass Fibre	Sep. Sheets	1.0	4	1.2	4
Other Materials				1.9	6
	total	**24.6**	**100**	**31.3**	**100**

Table 4.14: Manufacturing Inventory Data for SLA-Batteries [Murphy 2000]

	Item	**Quantity**
Input	Electricity	27,966 MWh
	Gas	647,860 cf
Output	Total Product Output Mass	20,345,000 kg

Table 4.15: Specific manufacturing inventory of SLA batteries (USA)

Item	**Specific Energy at Point of Use** $[\mathrm{Wh/kg_{Product}}]$	**Specific Primary Energy** $[\mathrm{MJ/kg_{Product}}]$
Electricity	1375	17.9[a]
Gas	10	0.0[b]
total		17.9

[a] Electric Energy at 27.7% total conversion efficiency for use in the USA [The Boustead Model 2000]

[b] 88.1% total conversion efficiency for use in the USA [The Boustead Model 2000]

4.2.6.3 Use Inventory

The use inventory is mostly determined by the following factors (LCPs):

ENERGY STORED The total energy of the use-phase fed into or taken out of the battery (also a DP) together with the efficiency are required to determine energy losses associated with the battery.

EFFICIENCY *Energy Efficiency* was described in Section 4.2.5.2 as 80% in the best case and 65% in the worst case (**Tab. 4.4**).

CYCLE LIFE The life cycle use is limited by the number of cycles that the SLA battery can undergo. In Section 4.2.5.3 this was described to depend on the depth of discharge which is described by **Eq. (4.15)** with the coefficients from **Tab. 4.6**.

MAINTENANCE *Maintenance* is taken to be zero as Sealed Lead Acid batteries are designed to be maintenance free.

MASS In cases where the batteries are required to be in motion in order to perform their function (e.g. in a car) then the *mass* influences the energy requirement of the vehicle, which has to be taken into account (inertia, increased friction).

Taking the above factors and other design requirements (maximum energy and power requirements to determine mass of battery, average depth of discharge, etc.) into account, an use-inventory can be estimated.

4.2.6.4 Post-Use Inventory

Retirement For lead acid batteries the retirement strategies include

- recycling of the material
- possibly remanufacture
- possibly reuse for application with lower design requirements and thus extending the useful life.
- Disposal

In the following the points are briefly described.

RECYCLING Material recycling is the most common retirement strategy for lead acid batteries, as the material is highly toxic. The recycling infrastructure has been established of the past and proven to be effective. Therefore between 80% and

90% of the lead and lead-alloys is recycled in Britain and above 90% in the USA [Wilson 1993, Bush 2000]. The energy requirement associated with lead recycling was reported as 4.85 MJ/kg of lead compared to 24.7 MJ/kg [1] for producing lead from virgin materials [Gaines & Singh 1995]. This is a factor 5 less energy required for recycling compared to using new materials.

In [Robertson, Wood, Ralph & Fenn 1997] the transport associated with recycling SLI lead-acid batteries was analysed. In **Tab. 4.16** the data is listed. Using this data, first the number of trips is estimated by dividing the nominal capacity of the respective truck by the mass transported by that type of truck. The results are listed in **Tab. 4.17**. Using this data and the average distance travelled, the total vehicle distance is determined, which is summarised in **Tab. 4.18**. Dividing the total distance travelled by the total mass transported, given in **Tab. 4.16**, and average distance for the respective mode of transport per unit mass of lead can be estimated.

Table 4.16: Deliveries of scrap batteries to a battery-breaking plant in the UK [Robertson *et al.* 1997]

Average Distance [km]	**Small truck**	**Medium Truck**	**Large Truck**	**Total**
	Mass Delivered [t] [a]			**[t]**
40	541	8,465	5,092	14,097
120	63	2,751	204	3,018
200	13	321	1,278	1,612
280	282	1,982	2,948	5,212
360	2	5	405	463
440	0	0	0	0
520	2	11	159	171
600	0	0	0	0
680	0	8	30	314
760	0	32	724	756
840	0	16	20	36
920	0	0	0	0
1000	0	0	0	0
Total	903	13,642	11,135	**25,679**

[a] In [Robertson *et al.* 1997] it is stated that the nominal capacities for the small, medium and large trucks are 3.6 t, 16 t and 30 t respectively.

The vehicle distance per unit mass of battery recycled **Tab. 4.18** was entered into The Boustead Model [2000] and from this it is estimated that the transport of lead acid batteries to the recycling plant requires about 4.22 MJ/kg of primary energy. Assuming that about 70% of the battery is lead and lead dioxide (see

[1] In [The Boustead Model 2000] this value is determined as 40.7 MJ/kg (average data from 1995).

Table 4.17: Vehicle trips to a battery-breaking plant in the UK

Average Distance [km]	**Small truck**	**Medium Truck**	**Large Truck**	**Total**
		Vehicle Trips		
40	150	529	170	849
120	17	172	7	196
200	4	20	43	66
280	78	124	98	300
360	1	4	13	18
440	0	0	0	0
520	0	1	5	6
600	0	0	0	0
680	0	1	10	11
760	0	2	24	26
840	0	1	1	2
920	0	0	0	0
1000	0	0	0	0
Total	251	853	371	**1,475**

Table 4.18: Vehicle distance to a battery-breaking plant in the UK

	Small truck (3.6 t)	**Medium Truck** (16 t)	**Large Truck** (30 t)
Vehicle distance [km]	31,229	332,301	1,665,442
Vehicle distance per mass of lead acid battery [km/kg]	0.035	0.024	0.150

Tab. 4.13) and that these are the only materials recycled, then this means that 4.22 MJ/kg for the battery, is 4.22 MJ per 0.7 kg of lead-alloy, or 6.03 MJ/kg of lead alloy. This value is slightly higher than the value reported in [Gaines & Singh 1995] and only includes the transport phase. On the other hand the data of Robertson *et al.* [1997] is for recycling small batteries, while Gaines & Singh [1995] concentrated on large batteries used in electric vehicles. Considering this the two values compare well. The energy associated with recycling lead is considerably less than that associated with virgin material and as lead is a highly toxic substance, that causes large impacts if released, recycling is a requirement, not an option.

REMANUFACTURE The author has not come across that lead acid batteries are remanufactured, but it may be a strategy that may be economically and technically viable in the certain cases.

REUSE As with the previous point, the author has not found any evidence that this is practised today, but it may be a possibility that may be viable in certain cases.

DISPOSAL Non-lead parts of the battery and the percentage not recycled must be assumed to end up to be disposed.

Disposal The two main final stages of parts of batteries include

- Incineration
- Landfill

Statistical data on average national percentages of industrial waste inventory (for industrial battery parts) and domestic waste inventory (for domestically used batteries) and impact data should be used here.

4.2.7 Limits and Applicability of Models

The limits of the inventories determined in this manner are that they must be seen as average inventories describing a product range at this time. They give a rough indication of what this technology is able to achieve (best case models, ULGPRM) and what is currently standard (upper limit specific product range models, ULSPRM). It should enable the designer to evaluate the order of importance of the different life cycle stages for specific design applications. The interpretation of the inventories will lead to valid conclusions, but they have to be revalidated at a later, more detailed stage of the design process.

The manufacturing and post-use inventories described here lack data, but they nevertheless show *how* the inventory is determined and illustrate the usefulness of the models when assessing the life cycle of a design concept.

4.2.8 Battery Models: Discussion

The outset of this case study was to derive models that represent the life cycle parameters as functions of design parameters, to establish a representative product material composition and to outline the inventory of the different life cycle stages.

The life cycle parameter *'mass'* is modelled as a function of the design parameters energy requirement and power requirement. In the case of batteries these two design parameters are correlated. This added a further degree of complexity to the model, which was overcome by using the mass specific energy and the mass specific power requirement. Thus the life cycle parameter 'mass' is included in the correlation of the two design parameters. The model was derived from empirical observations,

first established more than 100 years ago. Since the initial empirical model lead to a unsatisfactory correlation between the two design parameters, it was modified by adding one further constant. This, too, was determined empirically and was shown to satisfactorily correlate the two design parameters. The additional constant (a) is interpreted as lead acid batteries can supply a maximum energy ($1/a$) as the power requirement tends to zero. This interpretation is supported by the theoretical considerations and the data.

The mass specific energy and mass specific power data that was gathered during this project only gives a partial picture of all the lead acid batteries produced today. This explains why there are only few data points near the best-line. It is important though, that there are data points on or near the best-line, showing that the product really exists[2].

The life cycle parameter *'energy efficiency'* could not be modelled due to the lack of available data. General figures from literature sources are used instead.

The life cycle parameter *'cycle life'* is determined as a range from various sources depending on the depth of discharge. The model is empirical and was not backed up by theoretical considerations as time and data constraints did not allow a detailed analysis.

The *relative material composition* of lead acid batteries initially is derived from theoretical analysis, but practical limitations and manufacturers data have been taken into account to propose a generic relative material composition.

Finally it was shown how the complete life cycle inventory is determined. The design-parameter-dependent life cycle parameters, the relative material composition and design-parameter-independent life cycle parameters that are needed to determine the inventory. The so established inventory can be related to the pre-use, use and post-use phases.

Summarising, this case study has shown that:

- established relevant empirical relationships form a good starting point to determine the life cycle parameter model
- theoretical analysis together with practical considerations can be used to establishing the relative material composition of a generic product
- the best case model (ULGPRM) shows what the capability of lead acid batteries as a technology are at this moment in time with respect to the LCPs.
- the models for individual battery ranges (ULSPRMs, SPMs) from different manufacturers indicates the relative performance of the battery with respect

[2]In this case Optima produces batteries that lie on the 'best-line' [Hively 2000].

to what is possible and are interesting to the manufacturer and to designers, especially at later stages during the design process

4.3 Three-Phase Asynchronous Electric Motor

4.3.1 Background Information

The three-phase asynchronous motor, also called an 'Induction Motor', was first introduced in 1888 by Nikola Tesla [Encyclopædia Britannica 2000]. Since then it has evolved remarkably into a very efficient and widespread workhorse consuming a very large part of the worlds electrical energy.

The strength of the asynchronous motor is its simple construction combined with the potentially excellent efficiency during use. New developments in power electronics enabled the usually constant speed motors to be used in applications with variable speed requirements. New applications for these types of motors include electric fork-lift trucks and hybrid electric vehicles [Friedrich 1998].

The efficiency of any electric machine used a considerable amount of time is most important also from a cost point of view, as a motor that runs 24 hours per day over 15 to 20 year period will cost up to a factor 100 in terms of energy cost than what it cost to buy the product [Friedrich 1998].

4.3.2 Working Principles

A rotating magnetic filed is produced in the stator windings of the motor. In the simplest case this is achieved by arranging coils at 120° to each other in the stator. If a three-phase current is passed through, then each coil produces two magnetic poles, which rotate at the same frequency as the electrical frequency, f_{elec}. Therefore the synchronous frequency, f_{sync}, of the motor is [Gieck & Gieck 1996, Lindner, Brauer & Lehmann 1989]

$$f_{sync} = \frac{f_{elec}}{n_{Poles}} \ [Hz] \tag{4.17}$$

where n_{Poles} is the number of poles, which always have to be an even number equal or larger than 2. The synchronous speed is never achieved, though, because then the rotating field would have the same speed as the rotor and therefore the torque would be zero. But the torque may never be zero as at least the motor losses have to be overcome. The actual motor speeds for a 3-phase asynchronous motor connected to a 50 Hz supply are therefore slightly lower than the synchronous speeds. The actual speeds, f_{actual}, of a 3-phase asynchronous motor connected to a 50 Hz supply is displayed in **Tab. 4.19**.

Table 4.19: Actual motor speed at maximum load for a 3-phase asynchronous electrical motor driven by a 50 Hz supply (adapted from [Lindner *et al.* 1989])

Number of Poles	Synchronous Speed		Actual Speed at maximum Load
n_{Poles}	f_{sync} [Hz]	[rpm]	f_{actual} [rpm]
2	50	3000	2750—2970
4	25	1500	1350—1470
6	$16\frac{2}{3}$	1000	890—975
8	$12\frac{1}{2}$	750	680—725
10	10	600	540—580
12	$8\frac{1}{3}$	500	455—480
20	5	300	270—280
32	$3\frac{1}{8}$	188	175—178

The working principle of the asynchronous motors is briefly described in the following [Lindner *et al.* 1989]:

- The windings in the rotor are short circuited.
- The fluctuating magnetic field of the stator induced a fluctuating electrical voltage in the rotor even at standstill.
- The windings of the rotor with their induced current are deflected by the magnetic field of the stator and produce a torque.
- The induced voltage of the rotor decreases as the difference of the rotor frequency to the frequency of the magnetic field reduces.

4.3.2.1 Operating Conditions under Load

When the motor is required to produce torque then a specific current is required in the rotor. The current is induced in the rotor due to difference of the rotor frequency (which is the mechanical frequency) f_{mech} and the reduced electrical frequency f'_{elec}. The relative difference is called slip and is defined as

$$s = \frac{f'_{elec} - f_{mech}}{f'_{elec}} \quad \text{and} \tag{4.18}$$

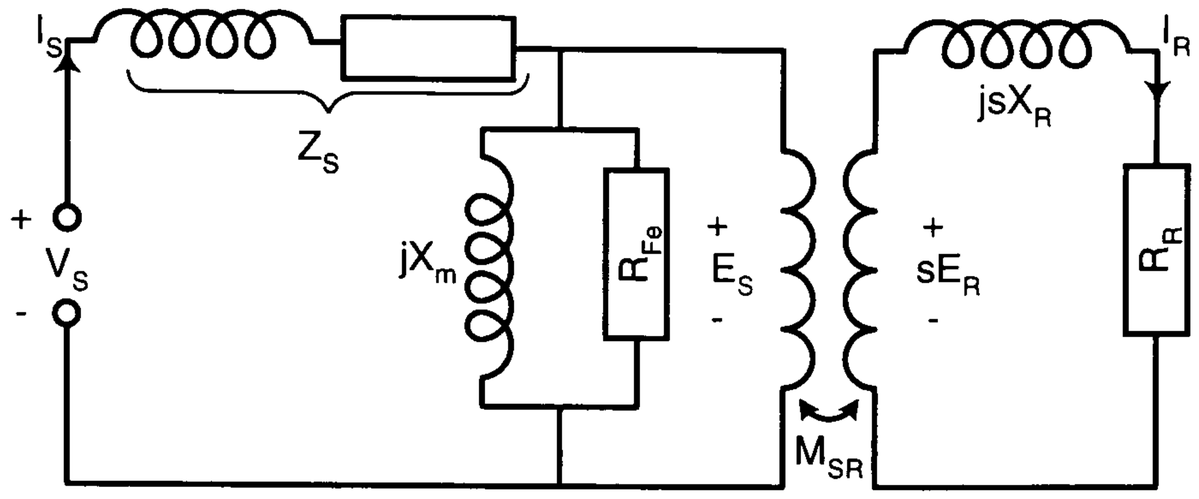
$$s = \frac{\omega'_{elec} - \omega_{mech}}{\omega'_{elec}} \tag{4.19}$$

The supplied electrical frequency f_{elec} is related to the reduced frequency by the number of poles, so that

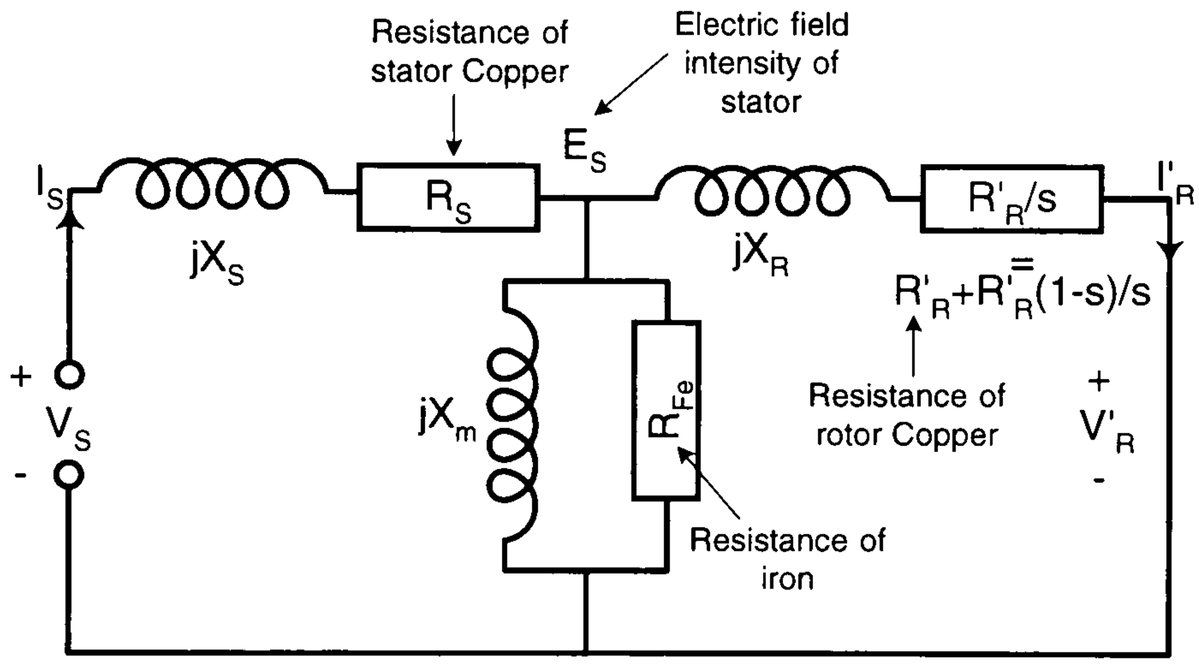
$$f_{elec} = \frac{1}{2} n_p f'_{elec} \quad \text{and} \tag{4.20}$$

$$\omega_{elec} = \frac{1}{2} n_p \omega'_{elec} \tag{4.21}$$

where n_p is the number of poles.



(a)



(b)

Figure 4.7: Induction Motor Equivalent Circuits (adapted from [Chalmers & Williamson 1991])

In **Fig. 4.7** (a) the circuit for mutual inductance is shown as a equivalent circuit for an induction motor and in **Fig. 4.7** (b) the equivalent circuit is shown referred to the stator coil. The magnetising impedance and iron losses of the induction motor are represented by X_m and R_{Fe} respectively.

Using the above figure, the power that is available to be converted to mechanical power is derived. The electrical power input comes from the three phase supply which is

$$P_{in} = 3V_S I_S \cos\theta \tag{4.22}$$

where V_S is the r.m.s. value of the phase voltage, I_S is the r.m.s. value of the phase current at the rated output with the power factor angle θ.

The stator copper losses are

$$P_{SCu} = 3I_S^2 R_S \tag{4.23}$$

while the iron losses are

$$P_{Fe} = \frac{3E_S^2}{R_{Fe}} \tag{4.24}$$

The power that is transferred across the air-gap is the difference between the input and the losses, i.e.

$$P_{AG} = \frac{3I_R'^2 R_R'}{s} = P_{in} - P_{SCu} - P_{Fe} \tag{4.25}$$

Then there are the rotor copper losses which are

$$P_{RCu} = 3I_R'^2 R_R' = sP_{AG} \tag{4.26}$$

Therefore the power that is available for being converted to mechanical energy is the power that is transferred across the air gap between the stator and the rotor reduced by the rotor copper losses.

$$P_{conv} = P_{AG} - P_{RCu} = 3I_R'^2 R_R' \frac{1-s}{s} \tag{4.27}$$

The output power is the converted power minus the windage and friction losses (P_{FW}).

$$P_{out} = P_{conv} - P_{FW} = T_{out}\omega_{mech} \tag{4.28}$$

Neglecting windage and friction losses and using **Eq. (4.28)**, **Eq. (4.19)** and **Eq. (4.21)** the torque produced under full load conditions is

$$\begin{aligned} T_{out} &= \frac{P_{out}}{\omega_{mech}} = \frac{P_{out}}{\omega_{elec}'(1-s)} \\ &= \frac{3\ I_R'^2\ R_R'\ n_p}{\omega_{elec}\ s} \end{aligned} \tag{4.29}$$

It can therefore be seen that *torque increases* with the

- the square of the rotor current referred to the stator from the rotor,
- the ohmic resistance R_R' referred to the stator from the rotor,
- the inverse of the electric frequency f_{elec},
- the inverse of the slip, the lower the slip under full load conditions (i.e. the more the mechanical frequency, f_{mech}, moves towards the reduced electrical frequency, f_{elec}', and therefore moves away from 1.0 towards zero) the larger the torque.

4.3.2.2 The Output Coefficient According to [Chalmers & Williamson 1991]

The concept of the output coefficient is described fully in [Chalmers & Williamson 1991]. It was found that it illustrates well the dependance of the design parameters with physical dimensions of the motor.

The output coefficient, C, is defined as the torque (P/ω) per unit Volume (D^2L) so that

$$C = \frac{P_{AG}}{\omega_{mech}\ D^2\ L} \tag{4.30}$$

where P_{AG} is the power supplied across the airgap, ω_{mech} is the rotor speed, D is the stator bore diameter and L is the stator core length.

In [Chalmers & Williamson 1991] it is shown that the output coefficient is proportional to the product of the maximum magnetic loading B^* and electric loading A^*, i.e.

$$C \propto A^*\ B^* \tag{4.31}$$

The electric loading, A^*, describes the rms-current per metre of periphery in [A/m] of the rotor and the magnetic loading, B^*, is the maximum air gap flux density in [T].

Assuming that all flux densities in the iron (B^*) and all the current densities in the copper (J) are kept constant, means that the losses per unit volume are constant at all points. Further the machine cross-section is kept the same, i.e. constant number of poles, slots and constant winding arrangement. This leaves only the stator bore diameter, D, and the core length, L, to be varied.

Since the cross-section is scaled with D then the cross-sectional area of a conductor, $A_{Conductor}$, scales according to

$$A_{Conductor} \propto D^2 \tag{4.32}$$

and therefore for a constant current density J in the rotor slot

$$\frac{I_R}{\text{slot}} \propto D^2 \tag{4.33}$$

but the slot pitch [3] is proportional to D, since the pitch increases with the circumference, which equals πD. Therefore the electric loading A^* is

$$A^* = \frac{\text{current}}{\text{arc length}} = \frac{\frac{\text{current}}{\text{slot}}}{\frac{\text{arc length}}{\text{slot}}} = \frac{\frac{\text{current}}{\text{slot}}}{\text{slot pitch}} \propto \frac{D^2}{D} = D \tag{4.34}$$

Therefore if the maximum flux densities in the iron (B^*) is kept constant then

$$C \propto A^*\ B^* \propto D \tag{4.35}$$

which means that the bigger the diameter the better the material is utilised for fixed densities, but there is a problem associated with cooling if the current densities are kept the same for big machines as for small. Assuming the thickness of the insulation of the winding is kept constant for all the diameters. Further assuming that the currents and voltages are referring to a constant number of turns, then the heat is conducted

[3] The slot length along the arc on the circumference.

according to $\dot{Q} = \lambda A \frac{\Delta T}{\delta}$, where λ is the conductivity, A is in this case the surface area of the conductor, ΔT is the difference in temperature between the inside of the insulator (closely linked to the conductor temperature) and the outside of the insulator (closely linked to the cooling medium properties and cooling medium temperature) and δ is the thickness of the insulator.

With the conductive thermal resistance defined as

$$R_{th} = \frac{\delta}{\lambda A} \tag{4.36}$$

The thermal resistance per unit length, R_{th}, between the copper and the ambient is mainly due to the 'air' and the electric insulation in the slot. The surface area of the conductor (A in **Eq. (4.36)**) increases with D so that $A \propto D$ and therefore

$$R_{th} \propto D^{-1} \tag{4.37}$$

Also the copper losses, P_{Cu}, are proportional to I^2R and the electrical resistance $R_{el} = \frac{\rho\, l}{A}$, where ρ is the specific electrical resistance, l is the conductor length and A is the conductor area. Therefore

$$P_{Cu} \propto \frac{I^2 \rho l}{A} \tag{4.38}$$

and as the stator copper windings run parallel to the rotor axis, l increases linearly with the rotor core length L and therefore the copper power loss per unit core length is

$$\frac{P_{Cu}}{L} \propto \frac{I^2}{A} \tag{4.39}$$

And as the current density in the copper is $J = I/A$ then

$$\frac{P_{Cu}}{L} \propto \frac{I^2\, A}{A^2} = J^2 A \propto J^2\, D^2 \quad \text{or the total copper loss is} \tag{4.40}$$

$$P_{Cu} \propto J^2\, D^2\, L \tag{4.41}$$

For a given temperature rise $\Delta T = \frac{\dot{Q}\,\delta}{\lambda\, A} = \dot{Q} R_{th}$, but here $\dot{Q}$ is due to the copper loss and therefore

$$\Delta T \propto J^2 D^2 D^{-1} \tag{4.42}$$

and for a given temperature rise[4], i.e. the temperature rise is a constant

$$J \propto D^{-\frac{1}{2}} = \frac{1}{\sqrt{D}} \tag{4.43}$$

This shows that for a given temperature rise a higher flux density can be carried in a smaller diameter motor. The overall effect on the electric loading, A^*, is that

$$A^* \propto D^{\frac{1}{2}} \tag{4.44}$$

[4]This is practically the long term thermal limit of the insulating material.

The iron losses lead to heat generation that can be more easily cooled and therefore the magnetic loading does not vary significantly with scale when looking at thermal considerations [Chalmers & Williamson 1991].

Therefore these effects lead to

$$C \propto A^* \propto D^{\frac{1}{2}} \tag{4.45}$$

i.e. there is an overall improvement in utilisation with increasing the diameter of the motor.

Knowing now that the current density also changes with the diameter according to **Eq. (4.43)** then the rotor current does not increase with D^2 as shown in **Eq. (4.33)** but it is reduced to

$$I_R \propto D^{\frac{3}{2}} \tag{4.46}$$

Also the generated voltage V_R for a constant maximum magnetic loading B^* is proportional to the air-gap area and therefore

$$V_R \propto DL \tag{4.47}$$

Therefore, as the power, P_{out}, of the motor is proportional to $V_R I_R$, it is also

$$P_{out} \propto D^{\frac{5}{2}} L \tag{4.48}$$

Using the Copper loss from **Eq. (4.41)** it can be seen that the the copper loss per unit power output follows

$$\frac{P_{Cu}}{P_{out}} \propto \frac{D^2\ J^2\ L}{D^{\frac{5}{2}}\ L} \tag{4.49}$$

and assuming that the current density $J \propto D^{-1/2}$ according to thermal considerations **Eq. (4.43)** then **Eq. (4.49)** becomes

$$\frac{P_{Cu}}{P_{out}} \propto \frac{D^2\ D^{-1}}{D^{\frac{5}{2}}} = D^{-\frac{3}{2}} \tag{4.50}$$

This shows that the copper losses per unit power are larger for smaller motors compared to larger motors which in turn will lead to an increased efficiency the larger the motors become.

Keeping the maximum flux densities in the iron (B^*) constant means that the iron losses, P_{Fe}, per unit volume are constant, therefore

$$P_{Fe} \propto D^2\ L \tag{4.51}$$

Using this relationship and comparing the iron loss, P_{Fe}, to the output power, P_{out}, it can be seen that

$$\frac{P_{Fe}}{P_{out}} \propto \frac{D^2\ L}{D^{\frac{5}{2}}\ L} = D^{-\frac{1}{2}} \tag{4.52}$$

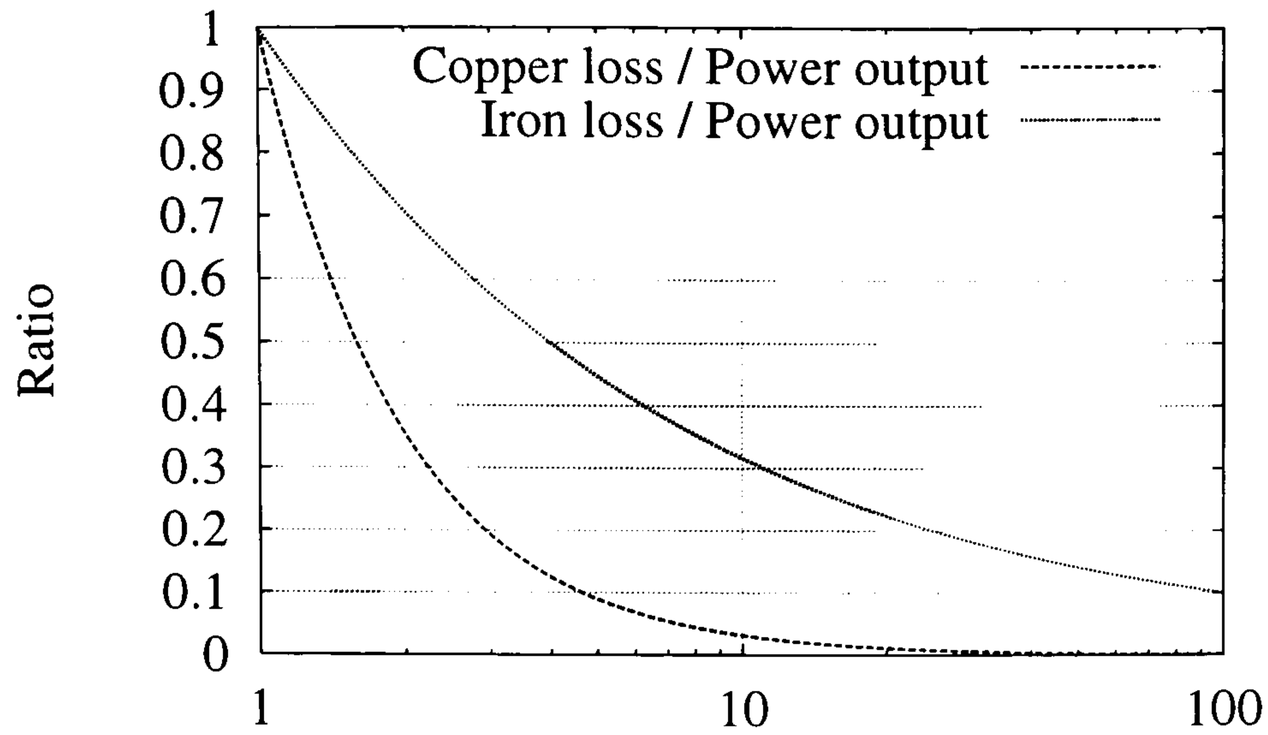


Figure 4.8: Plot of how the ratios of Copper losses to output and Iron losses to output power become less important as the motor becomes larger

The trends of reducing the relative copper and iron losses is shown in **Fig. 4.8**. It shows that the relative copper losses decrease at a larger rate than the relative iron losses. This shows that the copper losses are more important for smaller machines while the iron losses gain importance for larger machines

For the same cooling medium and constant speed the mechanical losses, P_{FW}, which include the windage and friction losses, behave according to [Chalmers & Williamson 1991] as follows:

$$P_{FW} \propto D^3 \, L \tag{4.53}$$

Efficiency, η, is the ratio of the available power over the total power put into the system; therefore

$$\begin{aligned} \eta &= \frac{P_{out}}{P_{out} + P_{Cu} + P_{Fe} + P_{FW}} \\ &= \frac{a \, D^{\frac{5}{2}} L}{a \, D^{\frac{5}{2}} L + b \, D \, L + c \, D^2 \, L + d \, D^3 \, L} \\ &= \frac{a \, D^{\frac{3}{2}}}{b + D \left(c + a \sqrt{D} + d \, D \right)} \end{aligned} \tag{4.54}$$

where a, b, c and d are constants. Differentiating this expression with respect to D and so making sure that the slope of η is always positive — i.e. that efficiency increases with motor size — gives:

$$\begin{aligned}
\frac{d\eta}{dD} &= -\frac{a\,D^{\frac{3}{2}}\left(c+a\sqrt{D}+d\,D+\left(d+\frac{a}{2\sqrt{D}}\right)\,D\right)}{\left(b+D\,\left(c+a\sqrt{D}+d\,D\right)\right)^2} \\
&\quad +\frac{3\,a\sqrt{D}}{2\,\left(b+D\,\left(c+a\sqrt{D}+d\,D\right)\right)} \\
&= \frac{a\sqrt{D}\,\left(3\,b+D\,\left(c-d\,D\right)\right)}{2\left(b+D\,\left(c+a\sqrt{D}+d\,D\right)\right)^2} \qquad (4.55)
\end{aligned}$$

The slope of η will be positive if the numerator is positive as the denominator cannot become negative considering that the constants (a, b, c, d) and the diameter (D) must be positive to have a physical meaning. Therefore

$$\begin{aligned}
a\sqrt{D}\,\left(3\,b+D\,\left(c-d\,D\right)\right) &> 0 \\
3\,b+D\,\left(c-d\,D\right) &> 0 \\
-d\,D &> \frac{-3\,b}{D}-c \\
d\,D^3 &< 3\,b\,D+c\,D^2 \quad \text{which means that} \\
P_{FW} &< 3\,P_{Cu}+P_{Fe} \qquad (4.56)
\end{aligned}$$

And it can therefore be seen that the friction and windage losses must be less than the sum of three times the copper losses and the iron losses [5] for the efficiency to increase with motor size. This is usually the case. This analytical consideration is reflected by real data as can be seen further on.

4.3.3 Motor Construction

The basic construction of typical three-phase motors are described in the following by listing the individual components.

ROTOR is typically copper wire wound on an iron core with a central steel shaft.

STATOR is cast iron, pressed steel or aluminium shell wound internally with copper wire on iron. The stator is ribbed to increase the area for cooling purposes.

BEARINGS (usually rolling element bearings but some types of motors have plain bearings) support the shaft

SHAFT carries the rotor and usually runs in rolling element bearings. In addition it carries a fan for cooling.

[5] In [Chalmers & Williamson 1991, p. 112] a different result is shown which could not be verified.

MOUNTING feet, flanges or pads.

STATOR FRAME incorporates the mounting features and may incorporate an enclosure to provide degrees of protection. These may range from drip-proof up to flame-proof which depend on operating conditions.

END-SHIELD is part of the frame and supports the bearings.

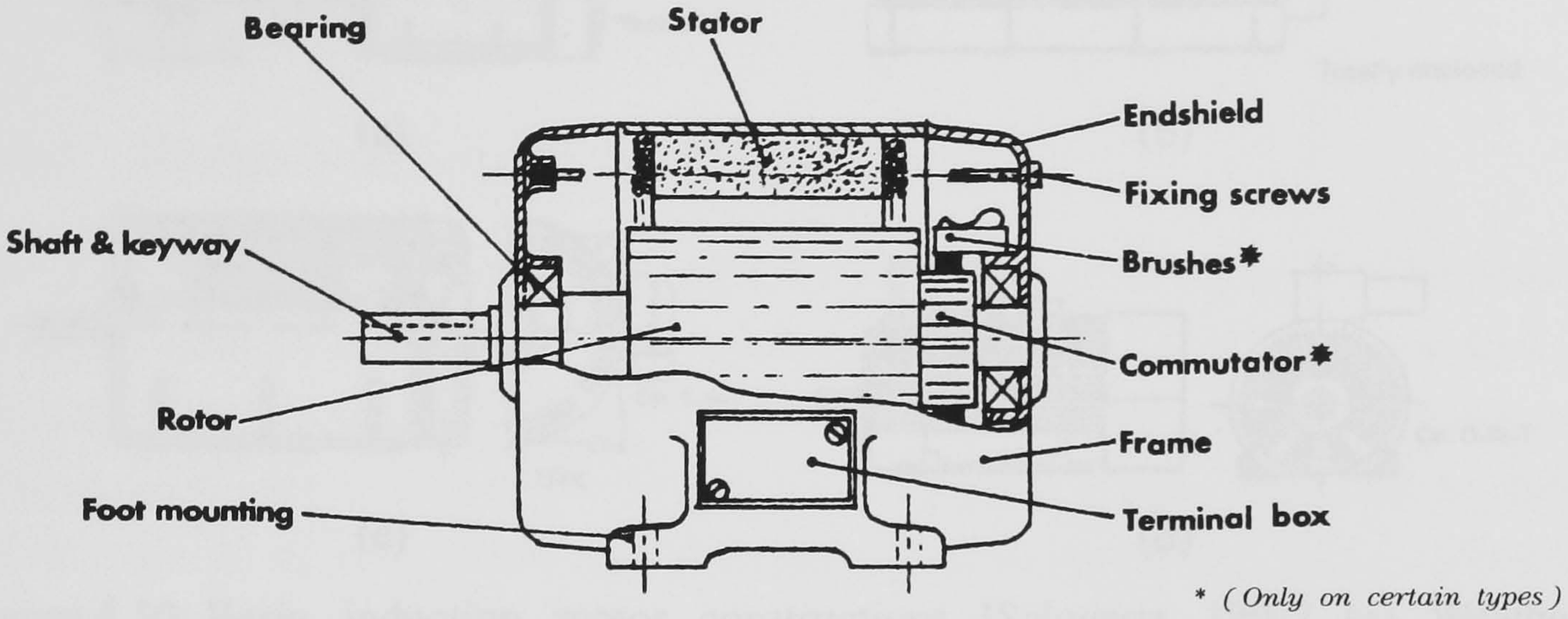


Figure 4.9: Part sectioned view of a typical electric motor [Mucci 1994]

Electric motors come in various forms and some are shown in **Fig. 4.10**. One of the most popular construction is the rib cooled (**Fig. 4.10** (d)). This type is further analysed in this section.

4.3.3.1 Standardisation

Dimensional standardisation is widely applied within mechanical design, as this allows considerable cost and variety reduction. For electric motors this is applied to the frame number which is equal to the height of the shaft axis above ground for the foot mounted configuration.

The preferred number series is based on decimal geometric series with a step change $\rho \approx \sqrt[b]{10}$, where b is a positive integer which shows how many numbers should be used to divide a decade. The preferred number, a_n, is a rounded result of

$$a_n \approx a_1 \cdot \left(\sqrt[b]{10}\right)^{n-1} \quad 1 < n < b \tag{4.57}$$

where you begin with $a_1 = 0.1$ or $a_1 = 1$ or $a_1 = 10$ or $a_1 = 100$ or $a_1 = \ldots$ depending which decade is used. A few preferred number series are shown in **Tab. 4.20**.

The axis height of the shaft, H, and the motor width, A (**Fig. 4.11**), follow approximately an R20 series (**Tab. 4.20**) [Pahl & Beitz 1996].

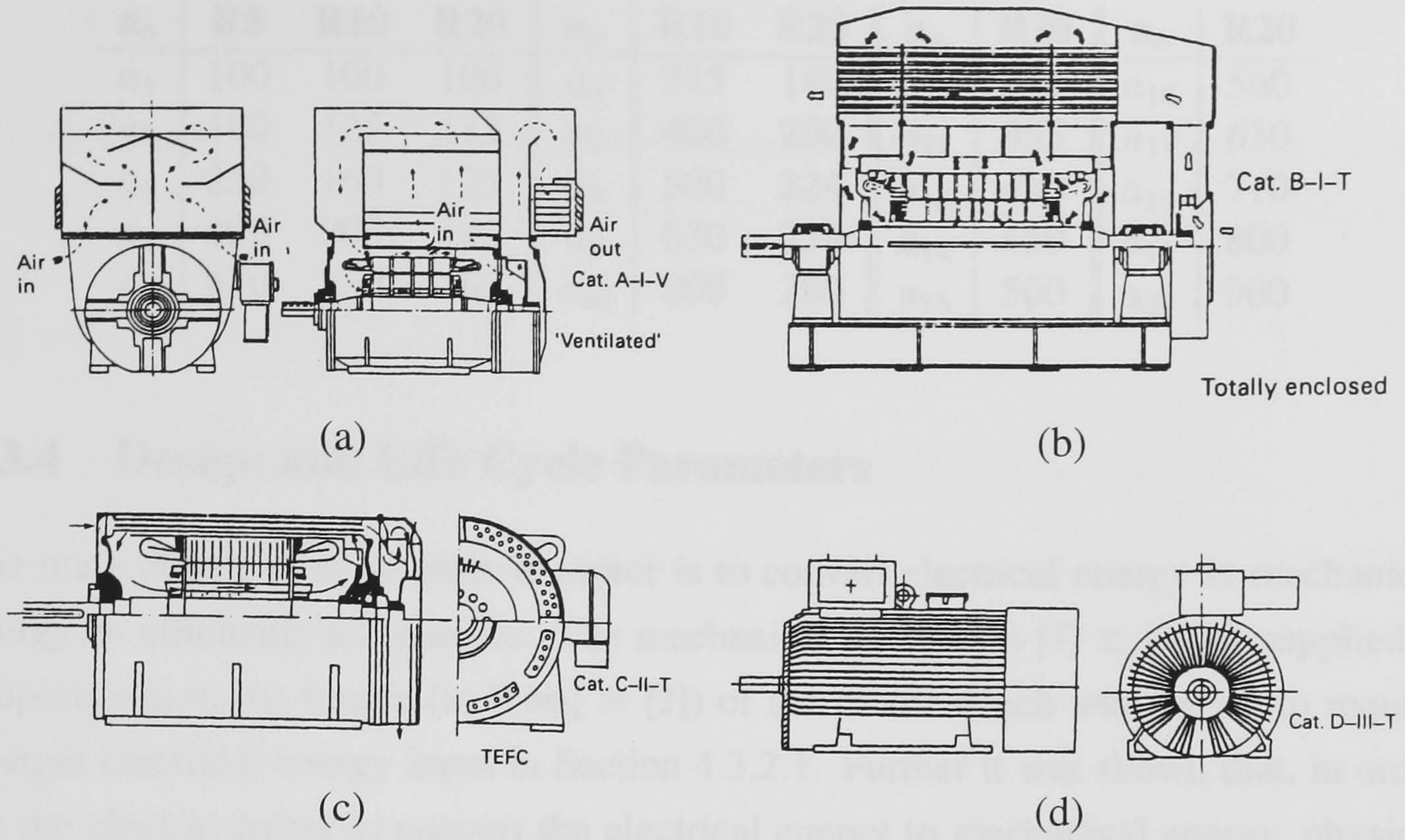


Figure 4.10: Basic induction motor constructions [Schwartz 1991] (a) Weather protected (open ventilated); (b) Closed-air-circuit-air-cooled (CACA); (c) Tube cooled (totally enclosed fan cooled [TEFC]); (d) Rib cooled (totally enclosed fan cooled [TEFC])

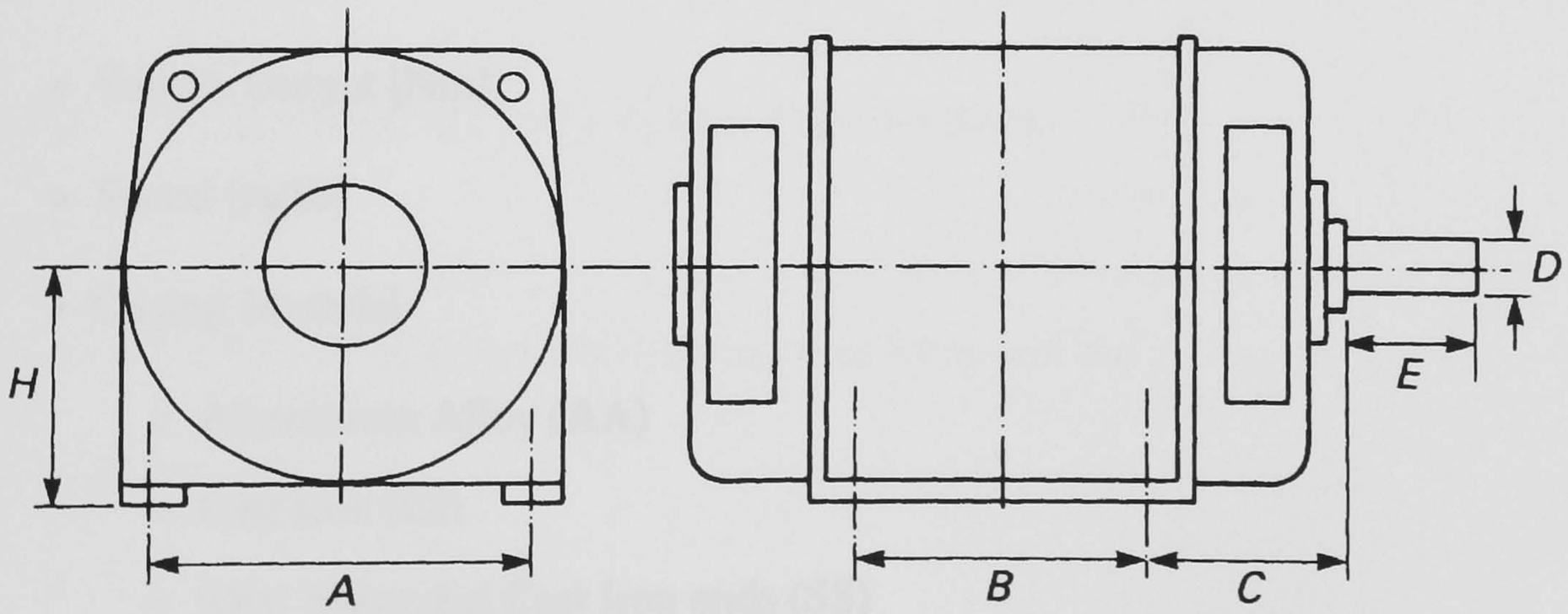


Figure 4.11: Standard symbols for the principle fixing dimensions of horizontal shaft motors [Schwartz 1991]

Table 4.20: Preferred Number Series for $a_1 = 100$ and $b = 5$ (R5), $b = 10$ (R10) and $b = 20$ (R20) (adapted from [Nor 1996])

a_n	**R5**	**R10**	**R20**	a_n	**R10**	**R20**	a_n	**R20**	a_n	**R20**
a_1	100	100	100	a_6	315	180	a_{11}	315	a_{16}	560
a_2	160	125	112	a_7	400	200	a_{12}	355	a_{17}	630
a_3	250	160	125	a_8	500	224	a_{13}	400	a_{18}	710
a_4	400	200	140	a_9	630	250	a_{14}	450	a_{19}	800
a_5	630	250	160	a_{10}	800	280	a_{15}	500	a_{20}	900

4.3.4 Design and Life Cycle Parameters

The main objective of an electric motor is to convert electrical energy to mechanical energy as efficiently as possible. The mechanical energy (in [J] $\equiv$ [Ws]) supplied is proportional to the torque (in [Nm] $\equiv$ [J]) of the motor which was shown to require a larger electrical energy input in Section 4.3.2.1. Further it was shown that, in order for the electric motor to convert the electrical energy to mechanical energy, physical parameters had to be satisfied. This means that in order to supply torque the motor must also fulfil constructional parameters.

It is therefore apparent that the design parameter *torque*, is linked to both the life cycle parameters *mass* and *efficiency*. It was further found that the constructional variations on the *casing* of the motor affect the mass. Furthermore the *speed* at which the torque is supplied influences the motor design by increasing the *number of pole pairs* to supply the torque at a lower speed for the same electrical frequency. This has an effect on both the mass and efficiency of the motor.

From the above considerations it can be seen that the design parameters are

- Torque Output [Nm]
- Speed [rad/s]
- Casing Material
  - Aluminium Alloy (AA)
  - Cast Iron (CI)
  - Steel Sheet and Cast Iron ends (SS)
- Design constraints due to standardisation and legislation
  - Standard Output Motors (SO)
  - High Output Motors (HO)

- Expected life
- Mass and/or volume of motor, especially if product is moving (e.g. hybrid electric vehicle)

All these parameters can be determined or chosen early on during the design phase. The parameter 'mass' is shown to be linked to other design parameters in the following sections, since it also is a life cycle parameter.

The life cycle parameters are the

- mass and specific material composition of an asynchronous motor
- efficiency of converting electrical energy to mechanical and viceversa (when operating as a generator)
- expected life
- other use related matters (e.g. maintenance)
- recyclability and actual recycling rates

A suitable database was found (EuroDEEM Catalogue) with relevant information of current European manufacturers of three-phase asynchronous motors [JRC & EC 1998]. The database included 3590 entries from 24 manufacturers. Not all the data was useful in that respect that some fields were blank or incomplete and therefore of no use.

From the EuroDEEM database 2413 entries where extracted and they represent 30 product ranges from 16 European manufacturers. This is summarised in **Tab. 4.21**.

4.3.5 Modelling the Life Cycle Parameters

4.3.5.1 Mass

As shown in **Fig. 4.9** the motor's three main elements are the

- Rotor,
- Stator and
- Frame/Casing,

which make up the majority of the inventory.

An increased torque output is achieved mainly by increasing rotor current (**Eq. (4.29)**) and the air-gap area (**Eq. (4.47)**). An increase in air-gap area requires the motor to

Table 4.21: List of asynchronous motors

Manufacturer	No. of Ranges	No. of Sub-Ranges	No. of Motors
ABB	5	24	459
ATB	1	4	78
Brook Hansen	3	12	177
EBM Werke	1	2	16
EFACEC	1	4	128
Fimet Motor	1	4	146
Georgii Kobold	3	7	61
Lafert-AEG	1	2	44
Leroy Somer	1	2	34
Marelli Motori	1	4	147
Rotor bv	4	16	489
Schorch EMA	2	8	174
SEW Eurodrive	1	1	21
Siemens	2	7	201
TEE	2	6	109
VEM	1	4	129
total	30	107	2413

increase in volume and since this also means that more materials are used the mass increases too. Also mechanical power P is the product of torque T and speed ω, therefore $T_{out} \propto P_{out}$, assuming constant speed. It was further shown that the power increases with the rotor diameter $D^{2.5}$ and the rotor length L (**Eq. (4.48)**). This means that the Power approximately increases with the rotor volume, and therefore the torque, T, increases with rotor volume, v_{Rot},

$$T_{out} \propto v_{Rot}^{c'} \tag{4.58}$$

where the exponent c' takes into account that torque is not proportional to the volume ($D^2\ L$) but to $D^{2.5}\ L$ and therefore lies in the region of $c' \approx 3.5/3.0 = 1.167$.

It can be further argued that with an increasing rotor volume, the casing and the stator have to increase proportionally. This clearly illustrates that the motor volume, v, (and therefore the motor mass, m, since $m \propto v$) increases with an increasing torque, or

$$T_{out} \propto m^{c'} \tag{4.59}$$

These theoretical considerations are reflected by the data as can be seen in the following.

The form the equations take, that relate mass to torque, is, following from **Eq. (4.59)**

$$m \propto T_{out}^{c} \tag{4.60}$$

where $c = 1/c' \approx 1/1.167 = 0.857$

From the data it was further found that an offset, a, is required. This offset reflects the fact that there seems to be a minimum mass required to even produce the smallest torque, which is a problem associated with scale. Therefore the equation that relates the life cycle parameter mass to the design parameter torque is

$$m(T) = a + b\,T^c \tag{4.61}$$

where a, b and c are constants.

Upper and Lower Limit Generic Product Range Models, (ULGPRM, LLGPRM) [JRC & EC 1998] Fitting the maximum and minimum data according to **Eq. (4.61)** yields values for the constants as listed in **Tab. 4.22**.

Table 4.22: Coefficients for best possible and worst Mass (kg) as a function of Torque (Nm) of three-phase induction motors for **Eq. (4.61)** (LLGPRM and ULGPRM) .

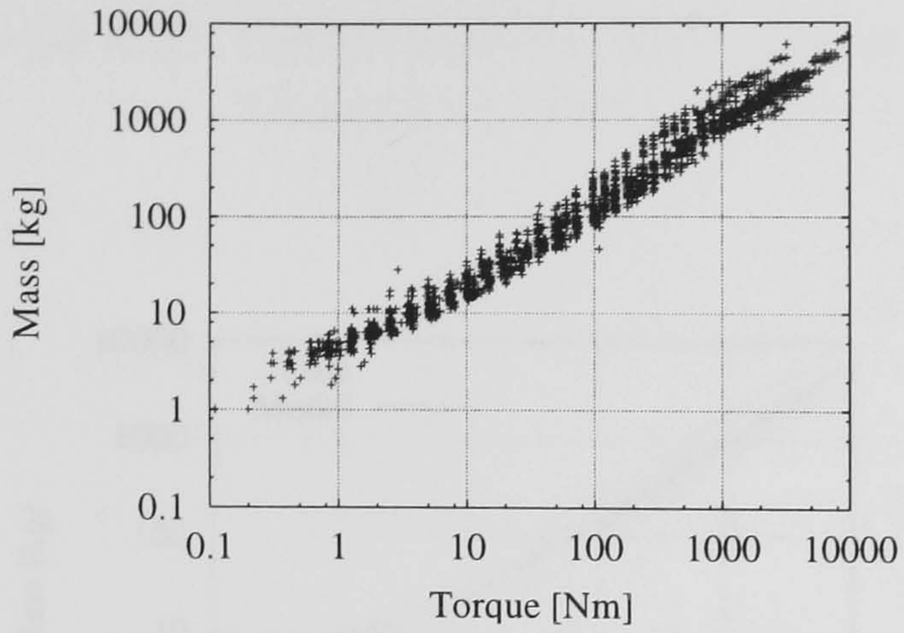
	Coefficient	**Value**
ULGPRM	a	0.6590
maximum mass	b	7.0960
(worst case)	c	0.7974
LLGPRM	a	0.6590
minimum mass	b	1.7920
(best case)	c	0.8388

As was shown in the previous pages, the exponent c of **Eq. (4.60)** should be about 0.857. Comparing this with the values of $c = 0.8388$ for the best case in **Tab. 4.22** and, more importantly, with models for individual ranges (see **Tab. 4.23**), shows that the values coincide reasonably well.

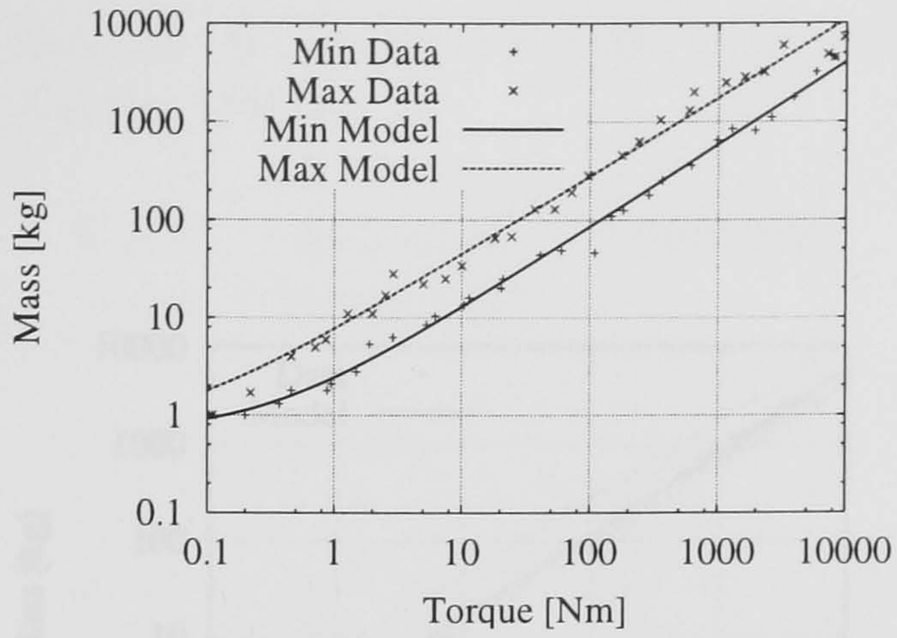
Specific Product Range Models, SPRMs (ABB, Siemens, VEM, [JRC & EC 1998]) The coefficients for **Eq. (4.61)** with respect to ABB, Siemens and VEM ranges are listed in **Tab. 4.23**.

The data and the models are shown in **Fig. 4.13**. It can be seen that these relatively simple models display good properties, in that the same type of model with different constants is able to describe the data. More sophisticated models are not required at this stage, but may be developed for more detailed analysis of these types of motors.

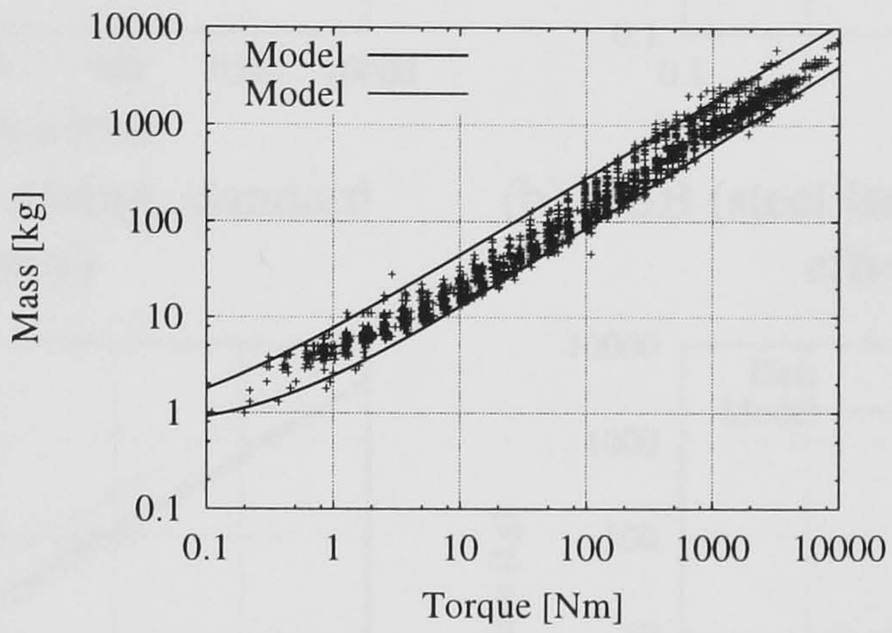
A further observation is that one SPRM was not sufficient for the Siemens aluminium casing, standard efficiency product range. The design of the large motors ($T > 250$Nm) is significantly different compared to the smaller induction motors resulting



(a) All data



(b) Extracted maximum and minimum data with respective models



(c) All data with maximum and minimum models

Figure 4.12: Maximum and minimum mass models for 3-phase, asynchronous electric motors based on **Eq. (4.61)** with the coefficients from **Tab. 4.22** and data from [JRC & EC 1998] (LLGPRM and ULGPRM)

in a different relationship between the the LCP mass and the DP torque. Therefore two SPRMs were employed to capture the difference.

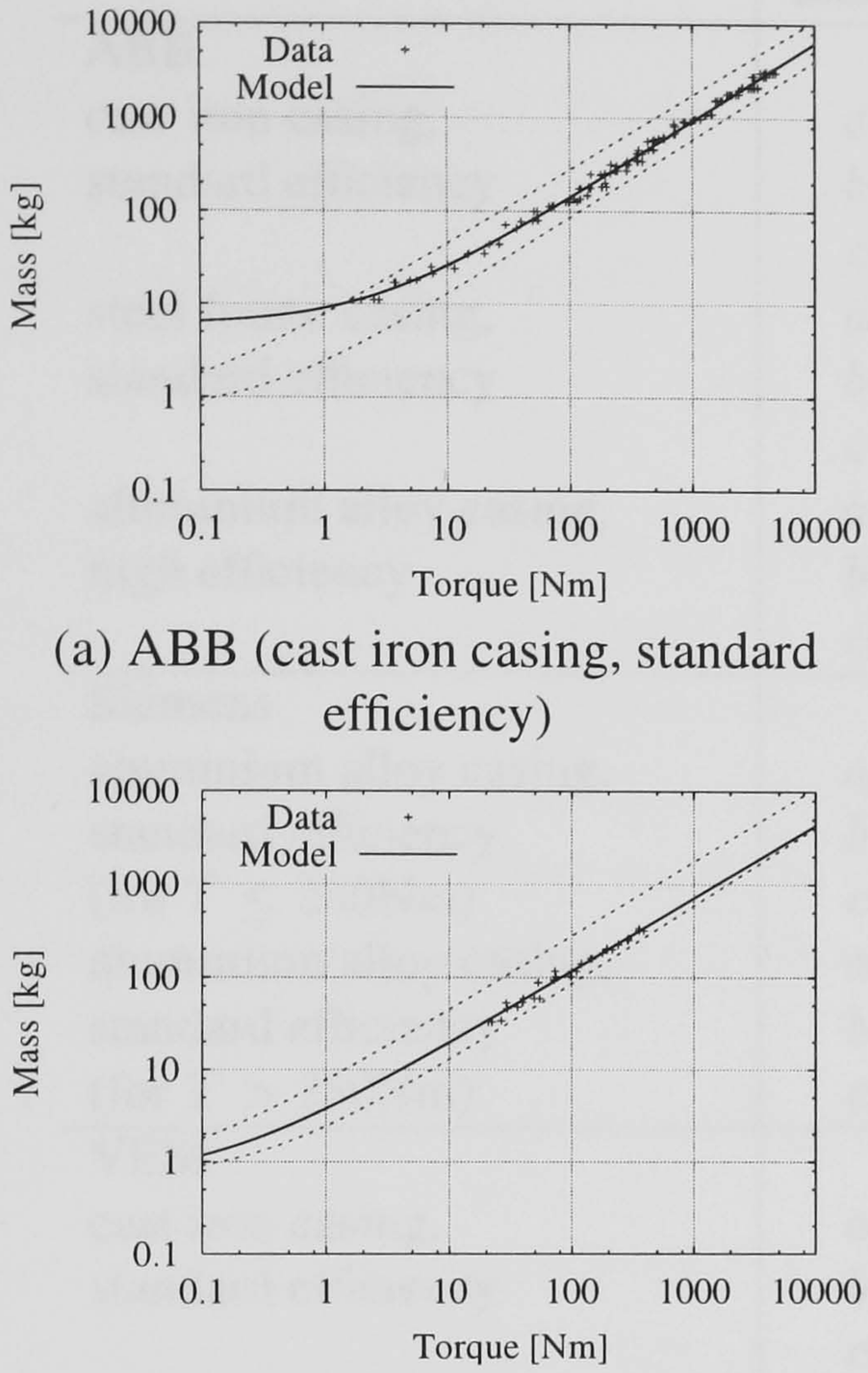
4.3.5.2 Efficiency

As shown in **Eq. (4.54)** the motor's three main losses are the

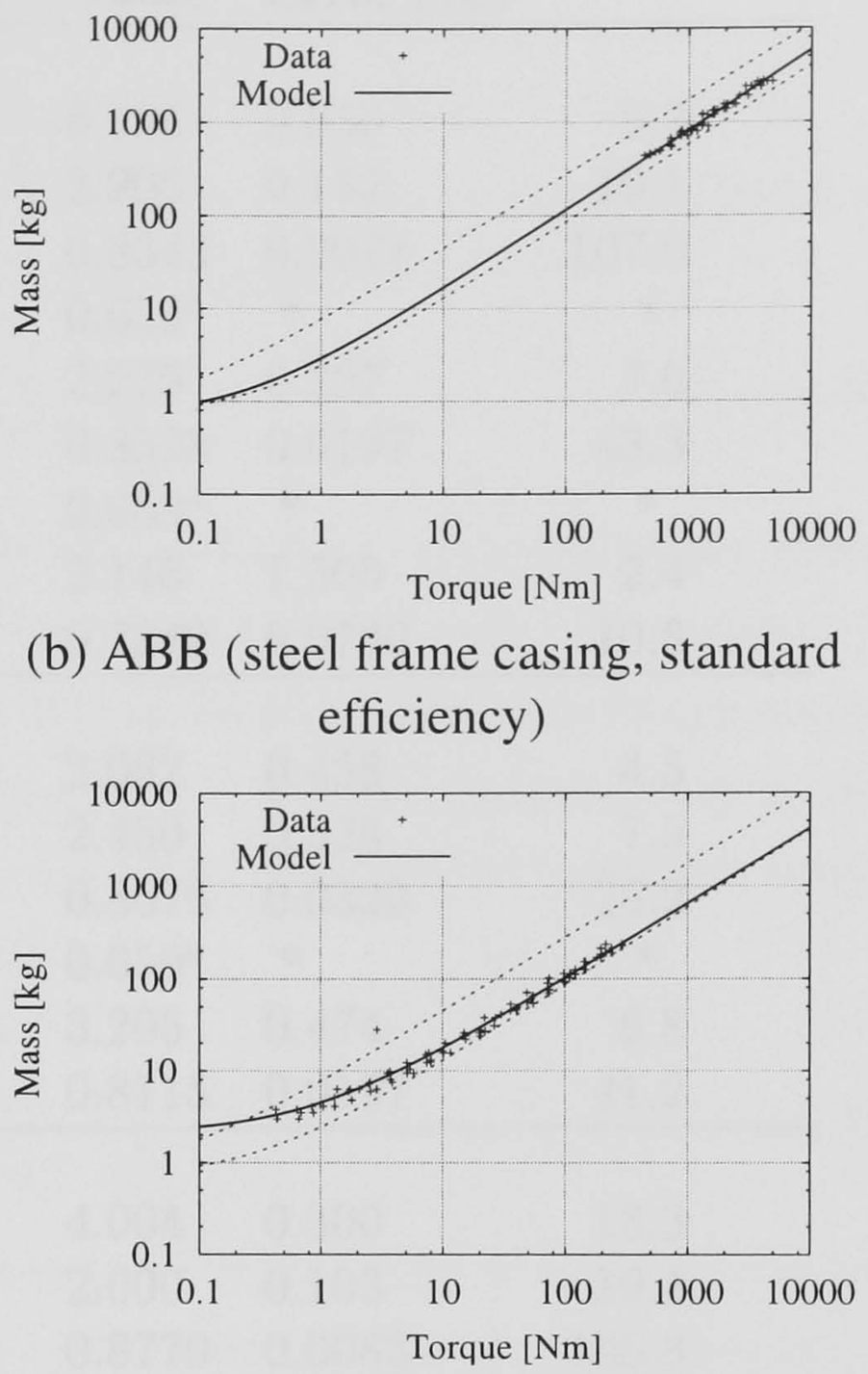
- Copper losses,
- Iron losses and
- Friction and windage losses,

which are responsible for reducing the efficiency.

It was shown that copper losses per unit power output are larger for smaller motors than larger motors (**Eq. (4.50)**, p. 133). It was further shown that the same is true for iron losses per unit power output (**Eq. (4.52)**). The difference is the rate at which the



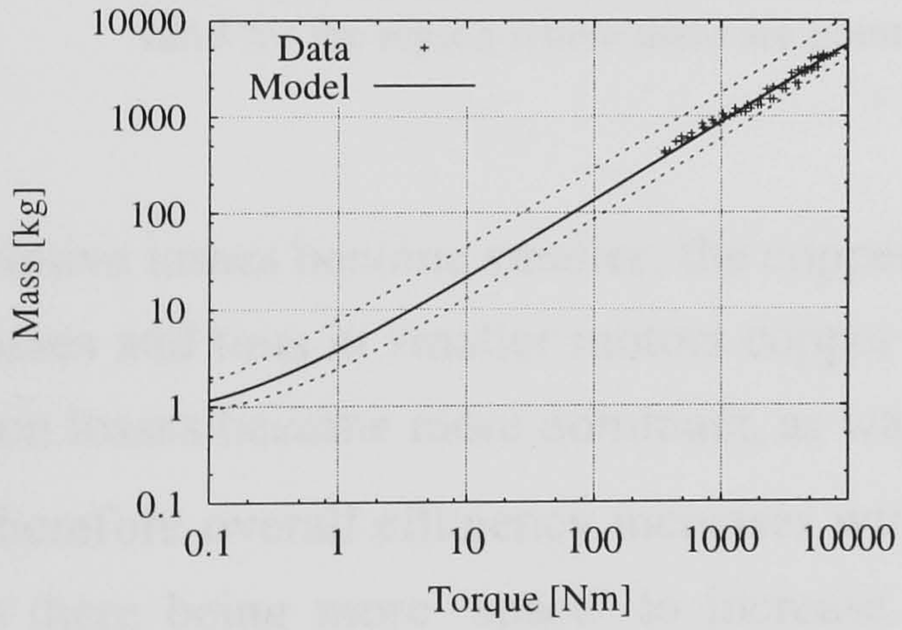
(a) ABB (cast iron casing, standard efficiency)



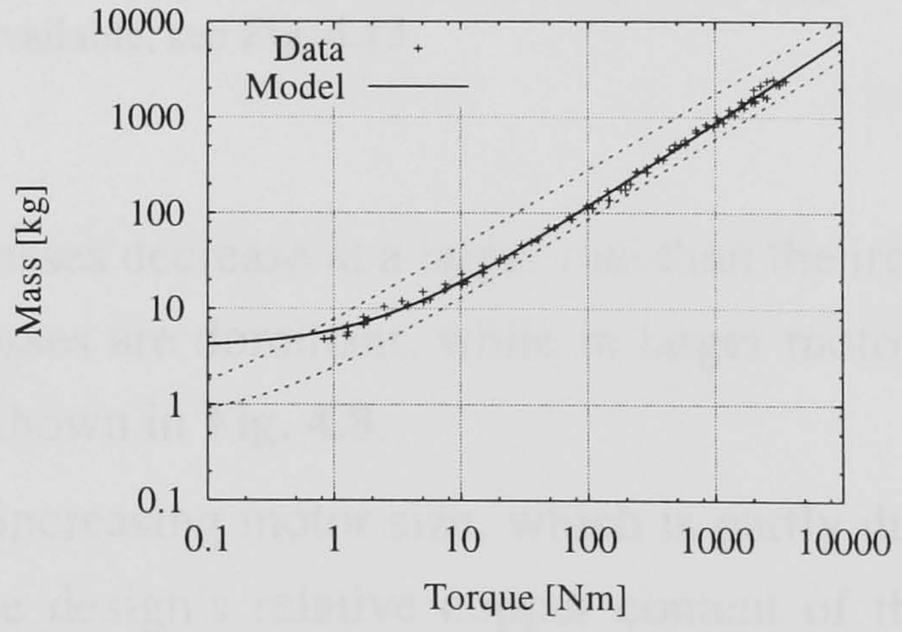
(b) ABB (steel frame casing, standard efficiency)

(c) ABB (aluminium alloy casing, high efficiency)

(d) Siemens (aluminium alloy casing, standard efficiency, for $T \leq 250$Nm)



(e) Siemens (aluminium alloy casing, standard efficiency, for $T > 250$Nm)



(f) VEM (cast iron casing, standard efficiency)

Figure 4.13: Mass models based on **Eq. (4.61)** with the coefficients from **Tab. 4.23** and data from [JRC & EC 1998] (SPRMs)

Table 4.23: Coefficients for Mass (kg) as a function of Torque (Nm) for some ABB, Siemens and VEM motors (**Eq. (4.61)**), SPRMs

Type	**Coefficient**	**Coeff. Value**	**Standard Error (SE)**	**Coeff./SE**
ABB				
cast iron casing,	a	6.106	0.656	9.3
standard efficiency	b	2.906	0.152	19.1
	c	0.8343	0.0078	107.0
steel frame casing,	a	0.659[a]	*	*
standard efficiency	b	2.279	0.327	7.0
	c	0.8528	0.0197	43.3
aluminium alloy casing,	a	0.659[a]	*	*
high efficiency	b	3.146	1.300	2.4
	c	0.7849	0.0730	10.8
Siemens				
aluminium alloy casing,	a	2.082	0.458	4.5
standard efficiency	b	2.450	0.328	7.5
(for $T \leq 250$Nm)	c	0.8076	0.0320	25.2
aluminium alloy casing,	a	0.659[a]	*	*
standard efficiency	b	3.205	0.474	6.8
(for $T > 250$Nm)	c	0.8115	0.0197	41.2
VEM				
cast iron casing,	a	4.004	0.300	13.3
standard efficiency	b	2.000	0.103	19.4
	c	0.8779	0.0083	105.8

[a]This value was fixed so that this model would not predict any better values than the 'best' model (LLGPRM). It has to be noted that the models for the individual ranges are only valid for the region where there are points available, see **Fig. 4.13**.

relative losses become smaller: the copper losses decrease at a larger rate than the iron losses and thus in smaller motors copper losses are dominant, while in larger motors iron losses become more dominant, as was shown in **Fig. 4.8**.

Therefore overall efficiency increases with increasing motor size, which is partly due to there being more 'space' to increase the design's relative copper content of the stator and to optimise other parameters such as the increased cross sectional area of the copper wire and conductor bars (reduces resistance) and reducing the operating flux densities.

It was shown in **Eq. (4.54)** how efficiency is the ratio of the power out over the power in. Also power is equal to torque times speed, $P = T\,\omega$. Therefore

$$\eta(T_{out}) = \frac{T_{out}\,\omega}{T_{out}\,\omega + T_{Cu}\,\omega + T_{Fe}\,\omega + T_{FW}\,\omega} \tag{4.62}$$

$$\eta(T_{out}) = \frac{1}{1 + \frac{T_{Cu}+T_{Fe}+T_{FW}}{T_{out}}} \tag{4.63}$$

Unfortunately power loss, torque loss, friction loss and windage loss data are not published by manufacturers. Even though the losses are known not to be constant with changing torque output, the equation is initially simplified to

$$\eta(T_{out}) = \frac{1}{a + \frac{b}{T_{out}}} \tag{4.64}$$

As expected, this equation does not satisfy the data sufficiently, since the torque losses, which are represented here by b are not constant, but also change with torque output. At this point it could not be anticipated how the torque losses change with torque output. Therefore trial and error has lead to the inclusion of a further constant c. By adding an exponent c to T_{out}, it was found that this is the best compromise between a simple model and accurate representation. Therefore

$$\eta(T_{out}) = \frac{1}{a + \frac{b}{T_{out}^{c}}} \tag{4.65}$$

where a, b and c are constants and T_{out} is the output Torque of the motor. The constant a should be equal or larger than 1 and b and c must be positive, so that efficiency is always less than 1. Ideally $a = 1$, but as there is no data available for such high torques where η theoretically becomes equal to unity, a is usually slightly larger than 1.

$$\lim_{T_{out}\to\infty} \eta(T_{out}) < 1 \text{ for } a \geq 1, b \in I\!R_{+}, c \in I\!R_{+} \tag{4.66}$$

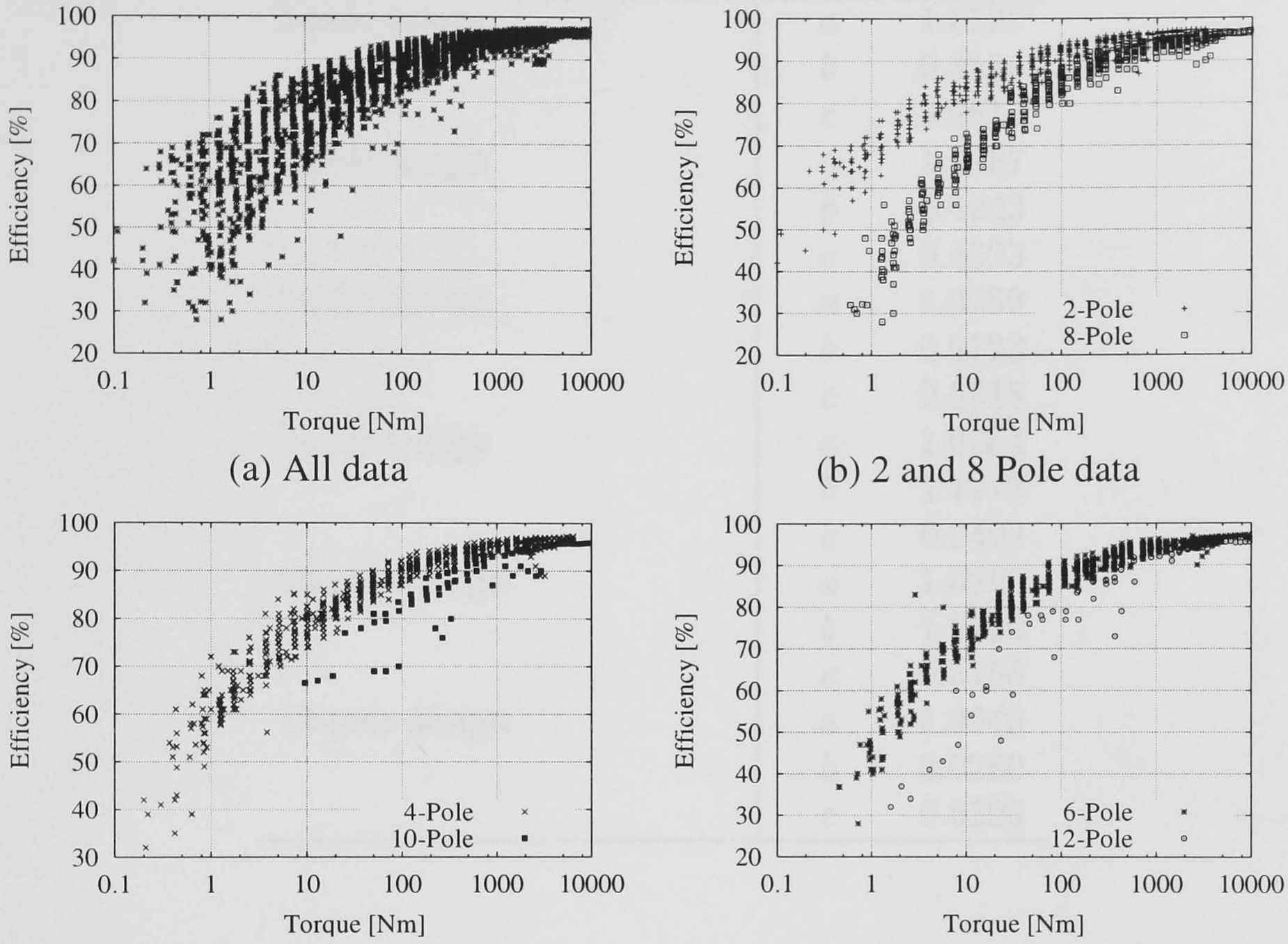
Comparing **Eq. (4.65)** with **Eq. (4.63)**, it can be seen that the constants b and c are linked to the sum of the torque losses $(T_{Cu} + T_{Fe} + T_{FW})$. It was further noted that usually c lies between 0 and 1, $0 < c < 1$. When writing **Eq. (4.65)** as follows

$$\eta(T_{out}) = \frac{1}{a + \frac{b}{T_{out}^{1}\,T_{out}^{c-1}}} = \frac{1}{a + \frac{b\,T_{out}^{1-c}}{T_{out}}} \tag{4.67}$$

it can be seen that the expression '$b\,T_{out}^{1-c}$' represents the sum of the torque losses. What can be seen here is that in absolute terms the losses increase with increasing output torque, but they do not increase at the same rate as the torque but to a power of less than 1, since $0 < c < 1$, i.e. at a lower rate than the torque. This was also reflected by the theoretical observations and by the data.

An interesting conclusion from this is that the systematic approach leads to a model where the coefficients have an actual physical meaning, and this should increase the value of these models for general conclusions on a technology as a whole.

Upper Limit Generic Product Range Models, (ULGPRM) [JRC & EC 1998]
Fig. 4.14 illustrates all the data plotted as efficiency against torque (a). It can be seen that the band, in which the data lies, is relatively wide. By taking into account a further relevant design parameter, Number of Poles, NP, it is illustrated that each band is much narrower and as the number of poles increase the efficiency decreases (b to d).



(a) All data

(b) 2 and 8 Pole data

(c) 4 and 10 Pole data

(d) 6 and 12 Pole data

Figure 4.14: Maximum efficiency data for 3-phase, asynchronous electric motors based [JRC & EC 1998]

In case the number of poles is not determined then the maximum efficiency is that of the 2-pole design. Otherwise the maximum efficiency for each case is illustrated in **Fig. 4.16**. The coefficients for the models are listed in **Tab. 4.24**.

Examining the coefficients a, b and c in **Tab. 4.24** it is interesting to note that the coefficients exhibit a trend depending on the number of poles. As the poles increase so do all the coefficients. In **Fig. 4.15** this behaviour can be clearly seen. This behaviour may be incorporated in a more complex model in future studies.

In **Fig. 4.17** all the models are plotted with all the relevant data. It can be seen that only a small percentage ($<1\%$) of *all* points lies outside the envelope.

Concluding on modelling the efficiency it can be seen that a simple model captures satisfactorily the trend of increased efficiency with increased torque output.

Table 4.24: Coefficients for Efficiency as a function of Torque (Nm) for 2-pole to 12-pole three-phase asynchronous motors (**Eq. (4.65)**), ULGPRMs

Type	**Coeff-icient**	**Coeff. Value**
2-pole design	a	1.0187
	b	0.3194
	c	0.4515
4-pole design	a	1.0167
	b	0.4943
	c	0.4523
6-pole design	a	1.0259
	b	0.9723
	c	0.5918
8-pole design	a	1.0254
	b	1.1970
	c	0.5493
10-pole design	a	1.0260
	b	1.6700
	c	0.5156
12-pole design	a	1.0349
	b	3.0280
	c	0.6293

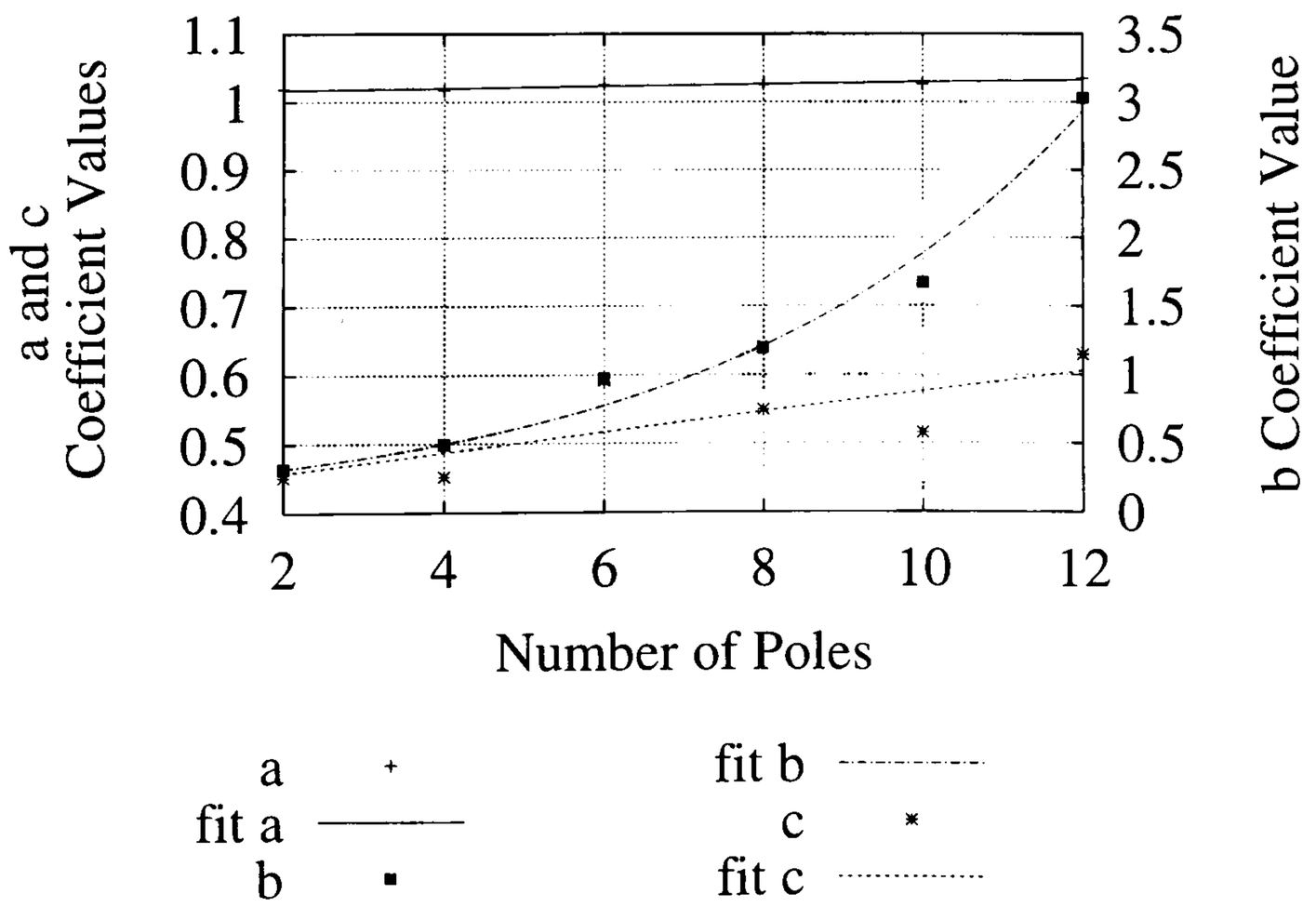


Figure 4.15: Coefficients from **Tab. 4.24** against number of poles

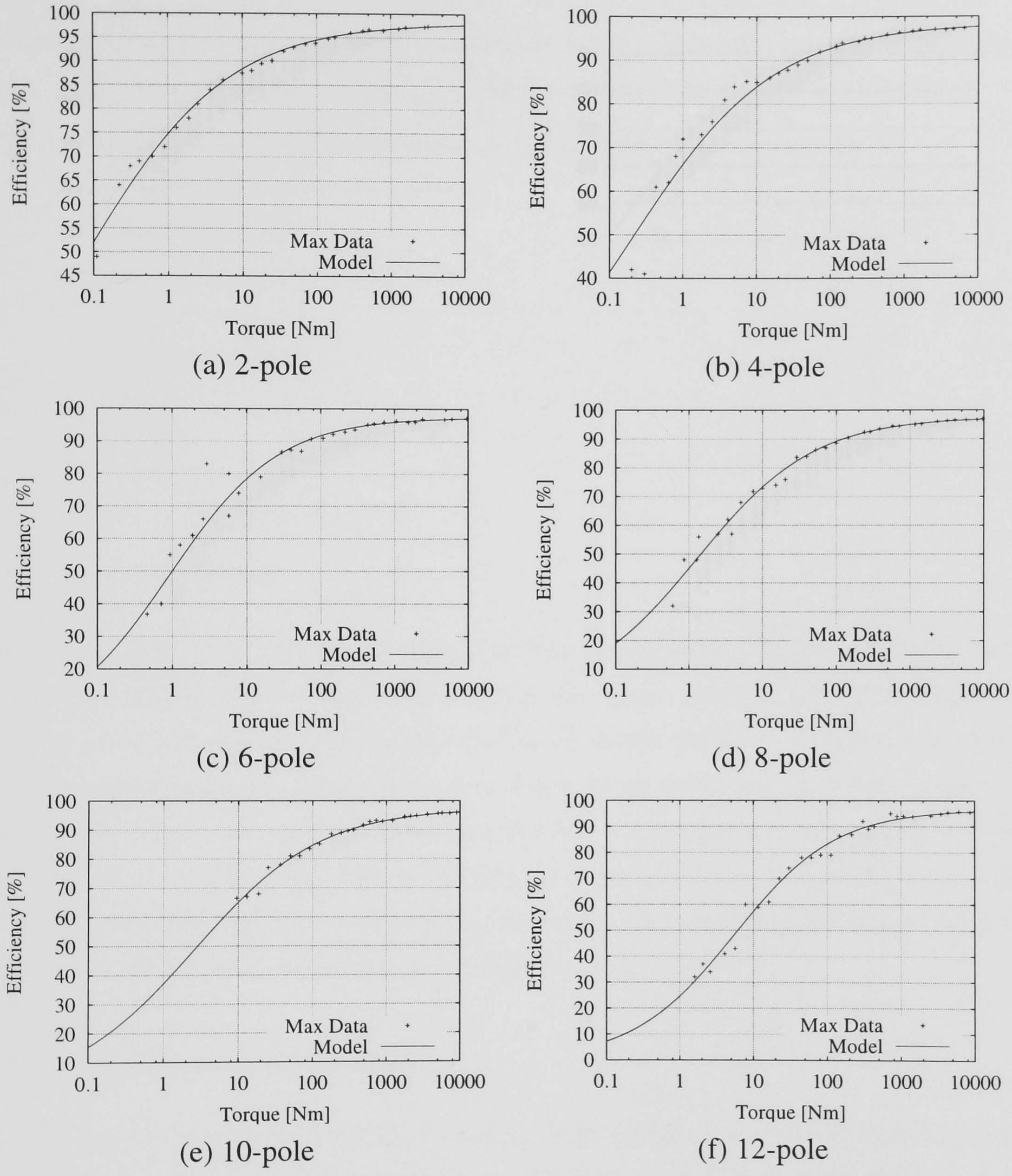


Figure 4.16: Maximum efficiency models for 3-phase, asynchronous electric motors based on **Eq. (4.61)** with the coefficients from **Tab. 4.22** and data from [JRC & EC 1998] (ULGPRMs)

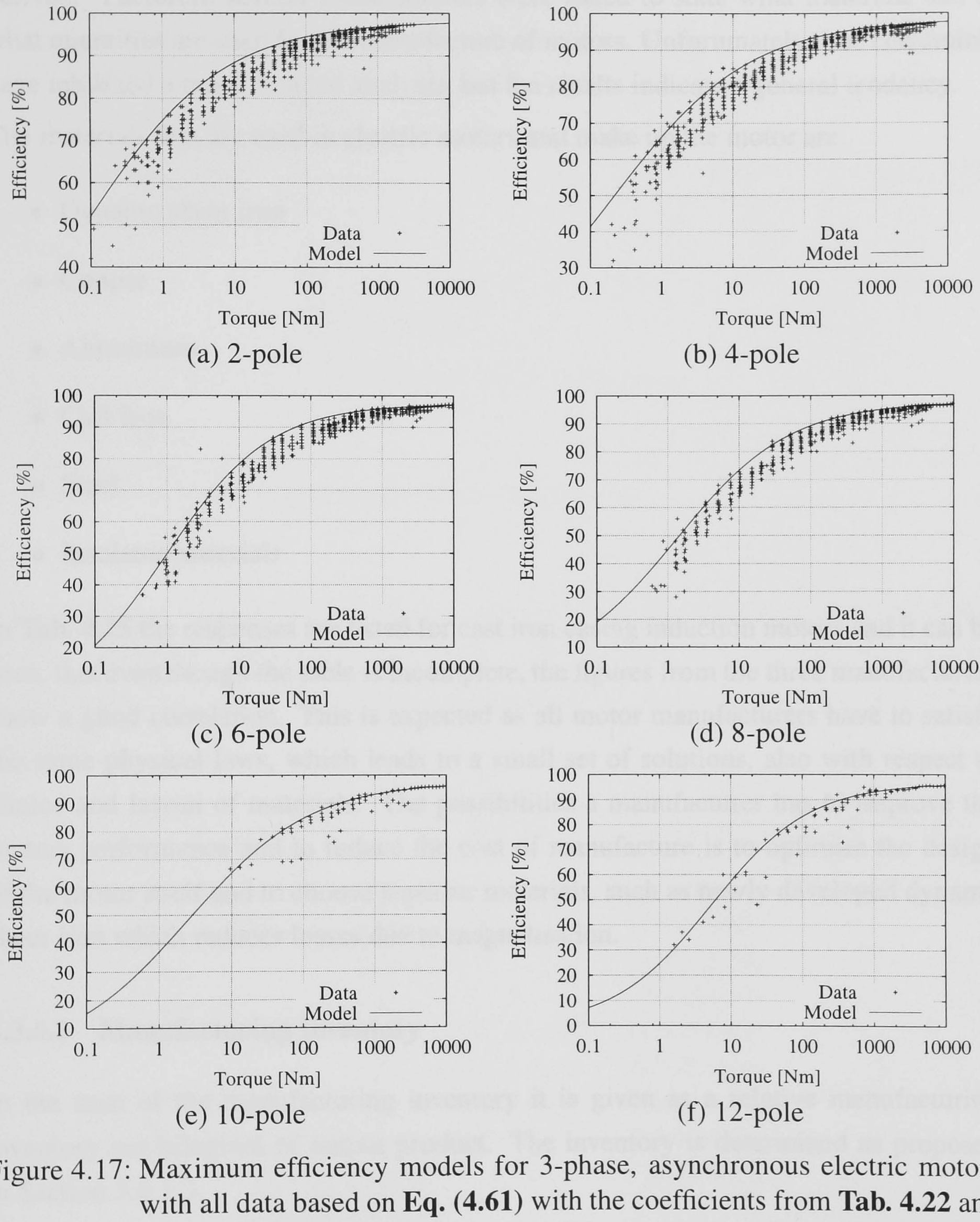


Figure 4.17: Maximum efficiency models for 3-phase, asynchronous electric motors with all data based on **Eq. (4.61)** with the coefficients from **Tab. 4.22** and data from [JRC & EC 1998] (ULGPRMs)

4.3.6 Modelling the Life Cycle Inventory

4.3.6.1 Relative Material Composition

The material that is required to make a 3-phase motor could not be theoretically derived. Therefore several manufacturers were asked to state what materials and in what quantities are used for the manufacture of motors. Unfortunately time constraints have inhibited a more detailed analysis, but the results indicate a general tendency.

The materials that are used in electric motors and make up the motor are

- Dynamo sheer iron
- Copper
- Aluminium
- Cast Iron
- Steel
- Insulator materials

In **Tab. 4.25** the responses are listed for cast iron casing induction motors and it can be seen, that even though the table is incomplete, the figures from the three manufacturers show a good correlation. This is expected as all motor manufacturers have to satisfy the same physical laws, which leads to a small set of solutions, also with respect to choice and layout of materials. The possibilities a manufacturer has to improve the motors performance and to reduce the cost of manufacture is to optimise the design of the motor itself and to choose superior materials, such as newly developed dynamo sheer iron which reduces losses due to magnetisation.

4.3.6.2 Manufacturing Inventory

In the case of the manufacturing inventory it is given as a relative manufacturing inventory per kilogram of output product. The inventory is determined as proposed in Section 3.6.1.3.

After consulting a number of motor manufacturers only *one* company was able to supply the required data in the time available. The figures listed in **Tab. 4.26** were reported by Henricson [1999].

The company makes almost everything in-house, including stamping and building the stator core, die-casting of rotors, shaft manufacturing, winding, assembling and testing [Henricson 1999].

Table 4.25: Generalised material composition of three-phase asynchronous electric motors with cast iron casings

Material	**Part**	**Percentage of Total Mass**		
		[Friedrich 1998]	[Harger 1999]	[Hui 1999]
Copper	Stator, Rotor	8%-11%[a]	7%[b]	5%-10%
Grey Cast Iron	Casing, Bearing Plate, Terminal Box, Foot	30%-35%	nd[c]	nd
Dynamo Sheer Iron	Stator	30%	34%[d]	25%-30%
	Rotor	10%	nd	nd
Steel	Shaft	10%	nd	nd
Other	Bearings, Insulation Materials	4%-12%	2%[e]	nd

[a]Lower value is for 2-pole design and upper value for 8 pole design.
[b]Stator only
[c]No data supplied
[d]Stator and rotor material
[e]Aluminium in the rotor and stator, otherwise no data supplied.

Information on the in-house waste, recovery and recycling rates was not supplied due to time constraints. In cases where the in-house recovery and recycling rates are not known, they could be estimated from averages of the particular industry or a related industry.

Table 4.26: Manufacturing Inventory Data for Electric Motors [Henricson 1999]

	Item	**Quantity**
Input	District heating	1500 MWh
	Electricity	8100 MWh
	Gas	390 MWh
Output[a]	63 cm shaft height	30,000 units
	71 cm shaft height	70,000 units
	80 cm shaft height	80,000 units
	90 cm shaft height	72,000 units
	100 cm shaft height	30,000 units

[a]All 282,000 units are from 0.25 kW to 4 kW Motors, 75% are 2-pole designs.

The output information from **Tab. 4.26** is not in terms of material quantities and therefore it is converted with an weighted average mass of the particular shaft height design as is shown in **Tab. 4.27**. The weighting of the mass is proportional to the ratio of the different pole designs to the total number of motors produced. In this case the

weighting is taken as 75% for masses of 2-pole motors and 25% of masses for 4 to 8-pole motors (see footnote in **Tab. 4.26**).

Table 4.27: Total product mass output using data from ABB [1998] and Henricson [1999]

Model	**Quantity [units]**	**Average Mass per Unit [kg]**	**Total Mass [kg]**
63 cm shaft height	30,000	4.5	135,000
71 cm shaft height	70,000	6.5	455,000
80 cm shaft height	80,000	10.0	800,000
90 cm shaft height	72,000	16.0	1,152,000
100 cm shaft height	30,000	23.0	690,000
total	282,000		3,232,000

The input information from **Tab. 4.26** is used to attribute the input to 1 kg of output product by dividing the input over the total mass product mass. This is the product mass specific input.

The information from **Tab. 4.26** and **Tab. 4.27** together with the relative material composition from **Tab. 4.25** and general data on the inventory of the materials extraction and production (as found in available LCI and LCA software) is used to gain a rough estimation of the complete pre-use inventory.

In **Tab. 4.28** it is shown how the manufacturing energy requirement is attributed per kilogram of output product. The result, which is that the manufacturing of a three-phase requires 22.8 MJ/kg of product output, is highly variable and depends on the actual place of manufacture and the actual energy requirements, which can vary significantly from one manufacturer to another. Further investigation is required to correlate the place of manufacture and the manufacturer to the specific primary energy requirement. The analysis shown here illustrates the procedure of establishing the manufacturing inventory and it is not extensively investigated, as it is not vital for this thesis to establish a comprehensive inventory of all the possible production routes.

4.3.6.3 Use Inventory

The use inventory is mostly determined by the following factors (LCPs)

OPERATING TIMES *Operating Times* are used to estimate the total power requirements and losses

Table 4.28: Specific manufacturing inventory (Sweden)

Item	**Specific Energy at Point of Use** [$Wh/kg_{Product}$]	**Specific Primary Energy** [$MJ/kg_{Product}$]
District Heating	464	2.1[a]
Electricity	2506	20.2[b]
Gas	121	0.5[c]
total		22.8

[a] Heating energy from CHP-plant at 80% total conversion efficiency (estimated from average performance of CHP [Beitz & Küttner 1990])

[b] Electric Energy at 40.5% total conversion efficiency (Sweden) [The Boustead Model 2000], part of electric energy (equal to heat energy from CHP with 40% of primary energy converted to electricity and 40% converted to usable heat [Beitz & Küttner 1990]) attributed to CHP at 80% total conversion efficiency (estimated from average performance of CHP [Beitz & Küttner 1990])

[c] 92% total conversion efficiency (Sweden) [The Boustead Model 2000]

POWER INPUT OR OUTPUT *Torque and Speed* requirements are used to determine the power required, together with the operating times and the efficiency the energy losses can be determined.

EFFICIENCY *Energy Efficiency* was described in Section 4.3.5.2 (p. 142). The function, **Eq. (4.65)** with the values from **Tab. 4.24**, relating the design parameters torque and number of poles to the efficiency is used to determine the efficiency.

LIFE The machine's life expectancy (service life) is usually expressed in mean time before failure (in Thousands of hours of operation). Manufacturers supply data with correction factors, depending on the type of operation (number of restarts, loading, etc.).

MAINTENANCE *Maintenance* is minimal for three phase induction motors. Average data should be determined and used. It will most possibly be negligible in normal circumstances.

MASS In cases where the motors are required to be in motion in order to perform their function (e.g. in a car) then the *mass* influences the energy requirement of the vehicle, which has to be taken into account (inertia, increased friction).

Taking the above factors and other design requirements (operating conditions, full load torque requirements to determine mass of motor) into account, an use-inventory can be estimated.

4.3.6.4 Post-Use Inventory

Retirement For three phase induction motors the retirement strategies include

- recycling of the material
- remanufacture
- reuse for application with lower design requirements and thus extending the useful life.
- Disposal

In the following the points are briefly described.

RECYCLING Many induction motors end up on scrap yards, which recover and separate the materials. Average values of industrial recycling rates of products with a high copper content need to be researched. The same applies to the remaining materials.

REMANUFACTURE Large motors (>100kW) are commonly remanufactured, i.e. the windings on the stator are rewired as generally the insulation material becomes degraded due to the heat during operation. It should be noted, although, that a motor with a rewound stator will not be as efficient as the original motor [Friedrich 1998]. This is due to a reduced copper density in the rewound motor, since it is most difficult to introduce the same amount of copper into the given space compared to when the stator is wound in a fully disassembled state.

REUSE A motor is reused, if it has sufficient service life left to justify the installation of the used motor. If the application is designed for a period which results in the motor not being used to the end of its service life then it may be assumed that the whole product can be reused. Therefore a proportion of the pre- and post-use inventory may be apportioned to the second phase of the motors life.

DISPOSAL Parts of the motor are not recycled end up to be disposed.

Disposal The two main final stages of a motor, or those part of it that are not recycled, include

- Incineration
- Landfill

Statistical data on average national percentages of industrial waste inventory (for industrial motor parts) and domestic waste inventory (for domestically used motors) and impact data may be used here.

4.3.7 Limits and Applicability of Models

The limits of the inventories determined in this manner are that they must be seen as average inventories describing a product range at this time. They give a rough indication of what this technology is able to achieve (best case models are the LLGPRM for mass and ULGPRM for efficiency) and what is currently standard (specific product range models, SPRMs). It should enable the designer to evaluate the order of importance of the different life cycle stages for specific design applications. The interpretation of the inventories will lead to valid conclusions, but they have to be revalidated at a later, more detailed stage of the design process.

The manufacturing and post-use inventories described here lack data, but they nevertheless show *how* the inventory is determined and illustrate the usefulness of the models when assessing the life cycle of a design concept.

4.3.8 Electric Motor Models: Discussion

The outset of this case study was to derive models that represent the life cycle parameters as functions of design parameters, to establish a representative product material composition and to outline the inventory of the different life cycle stages.

The life cycle parameter *'mass'* is modelled as a function of the design parameter torque. The model was derived from theoretical considerations and then slightly adapted by the addition of an offset to suit the data evidence. The offset may be explained by scaling problems, which means that small motors (below a size of about 0.8 Nm) are significantly different to the larger counterparts. In other terms, it means that below a certain size the motor does not become much lighter even thought the torque output is decreased.

It was shown that the data is highly banded, which allows the extraction of minimum and maximum points. These points represent the extremes of the life cycle parameter 'mass' for a given design parameter 'torque'. The models representing these extreme points clearly show what the current possibilities of induction motors are *today* in terms of mass when a specific torque is required. Sample models of individual product ranges show that the data is on a much narrower band, which is expected. These models are of interest to the manufacturers to indicate to them where they are compared to the current best and to designers during later phases of the design process, when it comes to selecting an actual motor.

The life cycle parameter *'energy efficiency'* was modelled as a function of the design parameters 'torque' and 'number of poles'. The model was based on the definition of efficiency and was simplified due to the lack of data and for practical reasons. It was shown that the data exhibits a clear upper boundary, representing what the best

induction motors can achieve in terms of efficiency. The number of poles, determining the operating speed together with the electrical input frequency, where shown to have an important effect on efficiency, which may be explored in more detail in future studies.

The *relative material composition* of the induction motors was determined by questioning manufacturers on their product range. The data from the manufacturers showed good agreement, but a more detailed study is required for a more differentiated picture. Then the influence of the casing material on the overall material composition, the influence of the number of poles and possible other influences can be determined. As a first rough indication the data represented here is considered sufficient.

The *manufacturing inventory* was determined from data reported by one manufacturer, by relating the energy input to the produced output. This allowed a relative manufacturing inventory per unit mass of the product. Here, too, more data (including emissions) is required for a more differentiated result.

Finally it was shown how the complete life cycle inventory is determined. The design-parameter-dependent life cycle parameters, the relative material composition and design-parameter-independent life cycle parameters are needed to determine the inventory. The so established inventory can be related to the pre-use, use and post-use phases.

Summarising, this case study has shown that:

- theoretical relationships form a good starting point to determine the life cycle parameter model
- questioning manufacturers about the relative material composition is useful to establishing the relative material composition of the generic product
- the best case models (mass (LLGPRM) and efficiency (ULGPRM)) show what the capability of three-phase induction motors as a technology are at this moment in time with respect to the LCPs.
- the models for individual motor ranges from different manufacturers indicates the relative performance of the motor with respect to what is possible and are interesting to the manufacturer and to designers, especially at later stages during the design process, when it is important to select a specific motor

4.4 Discussion

Two very different products were modelled in terms of design parameters to describe life cycle parameters. The discussion within their respective sections — for the lead

acid battery in Section 4.2.8 on p. 125 and for the induction motor in Section 4.3.8 on p. 155 — have highlighted the key points of the modelling case studies. In this section experiences and general points of modelling the LCI of actual products are discussed.

4.4.1 Procedure

Gathering information on raw materials and engineering materials is relevant within this context, since the inventories of the products list raw materials and energy requirements. Previous research works have discussed methods for obtaining inventory data on raw materials, engineering materials and energy generation in detail (see Section 2.4.4, p. 28, and Section 2.5, p. 44) and several commercially available LCI and LCA programmes have implemented results.

Carrying out the case studies has shown that after establishing the relationship between LCPs and DPs, the most work intensive part is to gather data from manufacturers. One of the first points of contact within a company are the sales personal. They only have data relevant to the sales of the product, which in many cases may be useful within this context, but as soon as more detailed data is required, specialised design, manufacturing and environmental personal needs to be addressed. Corresponding with companies, obtaining data, checking data and getting back with queries requires significant time and is a limiting factor to the practicality of this method, especially on a large scale. When describing the LCPs in Section 3.5.2.2 (p. 79), one criteria was that ideally LCP data should be obtained from publicly accessible data sources. In practical situation it was found that this is not always easy.

In case of the batteries, manufacturers sell batteries based on their energy and power performance. Most manufacturers therefore publish the relevant data, but sometimes only for a specific discharge rate and not for a range of discharge rates, as is required in this context. Often the performance is published in terms of current [A] and current $\times$ time [Ah], which is sufficient, if the average voltage is known.

The bulk of the data for the induction motors was gathered from a central database published by the Joint Research Centre and European Commission [JRC & EC 1998]. The motivation for setting up the database is the encouragement of designers by the European Commission to select energy efficient motors for their application. This is a good example of a third party publishing data on LCPs and DPs.

Data that is required for estimating the manufacturing inventory is not always publicly available. It is only available if a company publishes an environmental report. These are becoming more popular, especially in Germany, where the environmental report is published alongside the annual business report. Currently large companies of the automobile industry (e.g. DaimlerChrysler and Volkswagen) and of the chemical industry publish relevant information in their reports, but it is anticipated

that other companies will follow in the future. From the increasing public interest in environmentally related information, it can be expected that this trend will be increasingly observed in other European countries and throughout the developed world. Consequentially, the problems encountered when gathering manufacturing related information may decrease.

4.4.2 Comparison

The inventories of induction motors and batteries, which were estimated from general considerations and from data supplied by manufacturers, were not compared to the inventories of individual motors. This was not possible for financial and time constraints, since buying motors and batteries and analysing the quantities of materials requires substantial time and financial resources. This may be criticised, but it was considered that there is only a benefit when several ranges of products are analysed and averages are determined[6]. As this is quite impractical, the concept of a representative product was used, where the material content is estimated from manufacturers data and from theoretical and practical considerations. In future studies it is practical to reconfirm with several manufacturers, so that they may estimate to what percentage the estimate is correct with respect to the manufacturers product range. A relative comparison is sufficient in this context. During this study this was achieved due to time constraints.

The manufacturing inventory was obtained in each case study from one large manufacturer and is limited to the energy use during manufacture. This is not sufficient for a comprehensive estimation of the manufacturing inventory, but deemed adequate for the purpose of demonstration the modelling method. A comprehensive estimation of the relative manufacturing inventory per unit mass of product output, requires energy, waste stream and production data from several manufacturers from different regions. As was mentioned in Section 4.4.1 it will be easier to access information related to the manufacturing inventory, as more companies collect the data and publish it in environmental reports.

It is interesting to note that two products (battery and motor) from two countries (USA and Sweden) require similar primary energy requirements of the order of 20 MJ per kg of product manufactured.

The recycling inventory for batteries in Britain was compared to figures stated in the literature, which were for the USA and does not state whether it includes the transport phase, which is significant when recycling materials. Furthermore, the British recycling data is on small batteries while the USA recycling data is on large batteries

[6]E.g. 10 manufacturers from 2 continents produce 2 ranges, of which 5 products (from small to large) are analysed, results in 100 inventory analyses.

used in electric vehicles, which accounts for some of the difference. As with the previous point, the data is used for demonstration and recycling data requires more detailed analysis, differentiating regions and materials, for a comprehensive recycling inventory.

Comparing the models' predictions for the LCPs battery mass, induction motor mass and efficiency it is useful to distinguish between (reiterated from Section 3.5.6, p. 85):

- specific product model (SPM) for a single product,
- specific product range model (SPRM) for a product range from one manufacturer,
- upper or lower limit specific product range model (ULSPRM, LLSPRM), depending on the LCP, capturing the best of several products in one product range from one manufacturer and
- upper or lower limit generic product range model (ULGPRM, LLGPRM), depending on the LCP, capturing the best for a large number of products from many product ranges from several manufacturer.

The models are compared to the data that was used to determine the model. For comparison this is done in relative terms, i.e. what is the ratio (in this discussion called x) of the actual data to the model's predicted value ($x = \frac{\text{actual value}}{\text{predicted value}}$). A x-value of 100% means that the model's prediction is equal to the real data value.

The models' mean values of the ratio of the actual value to the predicted value is $\bar{x}$. The standard deviation, σ, is a measure of the spread of the individual points, x_i, from the mean, $\bar{x}$. The actual standard deviation is unknown and it is therefore estimated from the sample variance, $s^2 = \frac{1}{n-1}\sum_i (x_i - \bar{x})^2)$, where it is assumed that σ^2 is estimated by s^2 [Beitz & Küttner 1990]. The number of points, n, varies (between 15 for the specific battery models and 144 points for the specific induction motor range models) for the individual models. A Student t-distribution is utilised, which takes into account the larger spread of the distribution as a result of a low number of data and the associated unknown standard deviation. Assuming the Student t-distribution of the real values, the model's range that covers $(1 - \alpha)\,100\%$ of the real values is

$$x_{max,min} = \bar{x} \pm t_{1-\alpha/2,n-1}\sigma \tag{4.68}$$

where $1 - \alpha/2$ is the proportion that is covered in each tail of the 2-tailed interval. $(1 - \alpha)\,100\%$ is also the confidence level that $\alpha\,100\%$ of the points lie outside the 2-tailed interval. In this case 95% coverage is determined at a 95% confidence level, therefore $\alpha = 0.05$ and the $t_{1-\alpha/2,n-1}$ is determined from the Student t-distribution function for each model [Beitz & Küttner 1990].

The ranges that are determined from **Eq. (4.68)** for the different models and data sets are summarised in **Tab. 4.29**.

In the following the models' performances are summarised (all ranges specified cover 95% of the values at a 95% confidence level):

- The specific battery models (SPM) show very good correlations between the predicted values and the modelled values. The standard deviations for the modelled values are between 1.6% and 2.9%, 95% of the data values lie between 94% and 107% of the predicted values. The standard deviation is low as a specific product model captures the relationship of *one* specific battery.

- The actual values of the Hawker batteries lie between 85% and 106% (from $\bar{x} = 93\%$; $\sigma = 3.9\%$ to $\bar{x} = 100\%$; $\sigma = 2.8\%$) of the upper limit specific Hawker range model (ULSPRM). The standard deviation is relatively low as the individual batteries, from the same product range, exhibit similar characteristic relationship between the specific energy and the specific power.

- The upper limit generic battery range model (ULGPRM) determined from **Fig. 4.3** (p. 111, **Eq. (4.12)**, with coefficients from **Tab. 4.2**) was compared to the battery individual batteries. The actual values are between 37% and 94% (from $\bar{x} = 62\%$; $\sigma = 11.7\%$ to $\bar{x} = 68\%$; $\sigma = 12.3\%$) of the ULGPRM. The standard deviation is relatively large, as the real battery can deliver a significant lower specific energy for a high specific power, than what was derived from the data from [Ragone 1995]. For a low specific energy (<20 W/kg) the Hawker Batteries can deliver between 85% and 94% of the best battery model. This effect was described in Section 3.5.5 (p. 84), where it was illustrated that the individual product model or the product range model does not necessarily follow the ULGPRM or LLGPRM. Consequentially, the trend of the ULGPRM is *not* reflected in the relationship of specific power and the specific energy found in the individual batteries.

- The induction motor models represent whole product ranges (SPRM as opposed to the SPM of the batteries). The SPRM of the different induction motor ranges exhibit a reasonable spread around their mean values of 100%. The standard deviation ranges from $\sigma = 8.8\%$ to $\sigma = 14.5\%$ and consequently the maximum range of x is from $x_{min} = 71\%$ to $x_{max} = 129\%$.

- Comparing the induction motor ranges' data to the lower limit generic product range model (LLGPRM) determined in Section 4.3.5.1 (p. 139, **Eq. (4.61)** with constants listed in **Tab. 4.22**), the effect of the SPRM not following the LLGPRM described in Section 3.5.5 (p. 84) can be observed. As a result the

Table 4.29: Battery and electric motor models' statistics

Product (LCP)	**Model**[b]	$\bar{x}$	σ	**95% Coverage at 95% CL**[a] x_{min}	x_{max}
Battery (Mass via Specific Energy vs. Specific Power)					
Hawker (13Ah)	SPM	99%	1.6%	96%	103%
	ULSPRM	94%	2.7%	88%	99%
	ULGPRM	64%	11.8%	38%	89%
Hawker (16Ah)	SPM	99%	2.4%	94%	104%
	ULSPRM	93%	3.9%	85%	101%
	ULGPRM	62%	11.7%	37%	87%
Hawker (26Ah)	SPM	100%	1.6%	96%	103%
	ULSPRM	92%	1.8%	88%	96%
	ULGPRM	63%	10.7%	40%	86%
Hawker (42Ah)	SPM	100%	2.8%	94%	106%
	ULSPRM[c]	100%	2.8%	94%	106%
	ULGPRM	68%	12.3%	41%	94%
Hawker (65Ah)	SPM	100%	2.9%	94%	107%
	ULSPRM	93%	3.3%	86%	100%
	ULGPRM	64%	12.0%	38%	90%
Induction Motor (Mass)					
ABB, Cast Iron standard efficiency	SPRM	100%	10.8%	79%	121%
	LLGPRM	212%	28.1%	157%	268%
ABB, Steel standard efficiency	SPRM	100%	8.8%	82%	118%
	LLGPRM	190%	18.2%	154%	227%
ABB, Aluminium high efficiency	SPRM	100%	10.3%	78%	120%
	LLGPRM	164%	17.1%	139%	199%
Siemens, Aluminium standard efficiency, (for $T \leq 250$Nm)	SPRM	100%	12.0%	76%	124%
	LLGPRM	150%	22.9%	104%	196%
Siemens, Aluminium standard efficiency, (for $T > 250$Nm)	SPRM	100%	14.5%	71%	129%
	LLGPRM	199%	28.8%	138%	259%
VEM, Cast Iron standard efficiency	SPRM	100%	10.2%	80%	120%
	LLGPRM	185%	28.0%	129%	240%

[a] Confidence Level

[b] SPM is the Specific Product Model
SPRM is the Specific Product Range Model
ULSPRM is the Upper Limit Specific Product Range Model
LLSPRM is the Lower Limit Specific Product Range Model
ULGPRM is the Upper Limit Generic Product Range Model
LLGPRM is the Lower Limit Generic Product Range Model

[c] This battery represents the upper limit of the Hawker range, therefore values are same as for SPM

standard deviation is large with the maximum being $\sigma = 28.8\%$. The range of x is covered from $x_{min} = 104\%$ to $x_{max} = 268\%$.

This summary illustrates that the LCPs can be predicted with an increasing accuracy the more specific the model is that is utilised for the prediction. It can be seen that the more general the prediction is the larger is the spread (represented by the standard deviation σ) within which the solution lies (see **Fig. 4.18**). The standard deviation of the models may be used in sensitivity analyses, to assess the relative importance of the LCP on the overall inventory or the impacts.

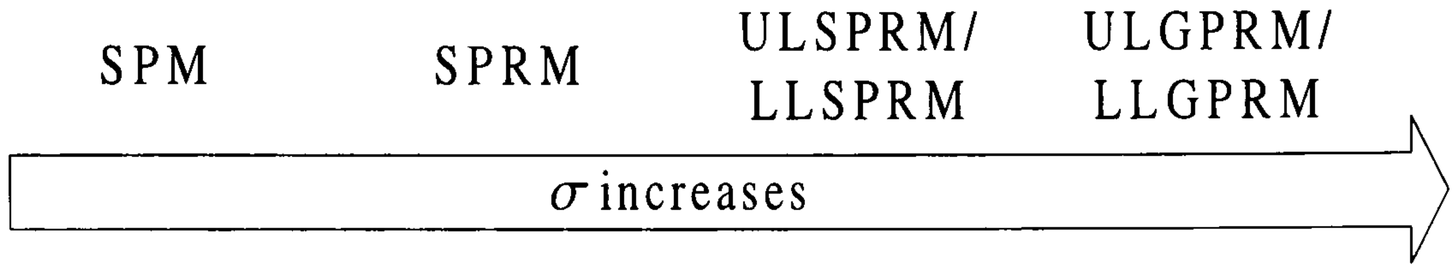


Figure 4.18: Increasing standard deviation (σ) depending on type of model used to predict value for LCP

5 Applying the Models: Concept Evaluation of a Hybrid Electric Vehicle

5.1 Overview

This chapter is intended to illustrate how the models are intended to be used to evaluate the life cycle inventory at the concept stage. The design concepts analysed here are of two types of the power train layout for hybrid electric vehicles, namely a

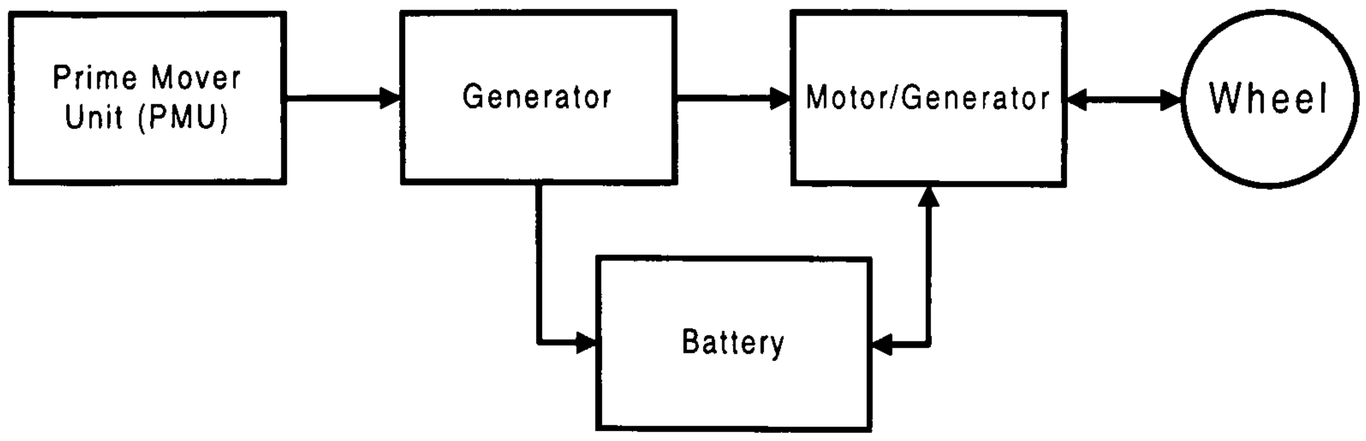
- series configuration and
- parallel configuration

The configurations are illustrated in **Fig. 5.1**. it can be seen that a series configuration requires an additional generator compared to the parallel layout. The advantages and disadvantages that are associated with the two configurations are discussed briefly and the energy consumption during the use-phase is analysed. A study has shown that in the case of a medium sized passenger car, that is used 200,000 km over a ten year period, the use-phase contributes more than 65% of the total energy requirement [Hoffmann 1995]. It is a safe assumption that in the case of commercially used vehicles this ratio will increase even further. Therefore analysing the use-phase of such a vehicle and reducing the energy requirement during that phase will have the largest impact on the overall life cycle energy requirement.

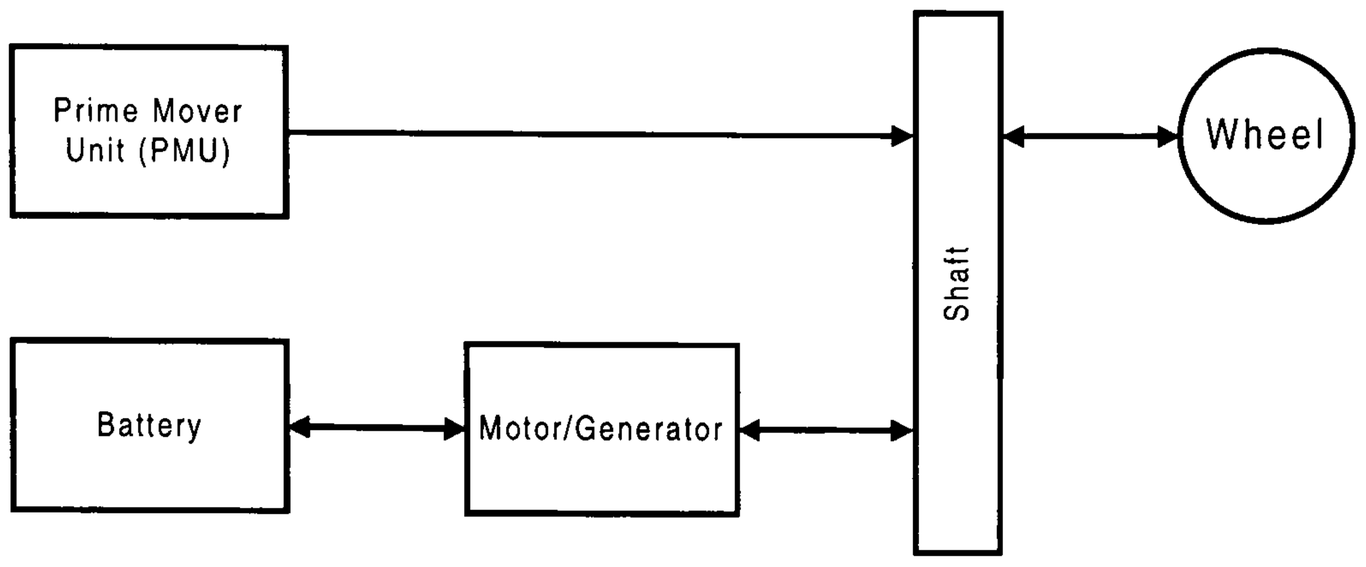
The concept is evaluated in terms of primary energy requirements and untreated waste streams (emissions). But the scope of this work does not include an impact assessment.

In Appendix A.1 it is explained how the simulation was implemented and verified. Furthermore the findings of a parametric study are explained, where the relative importance of various design parameters are investigated.

In the following the case study is introduced



(a) Series



(b) Parallel

Figure 5.1: Electric hybrid vehicle configurations (arrows indicate direction of energy flow)

5.2 The Case Study

The case study chosen here is a urban passenger bus. It is investigated what the untreated waste streams are, that are associated with the two concepts of drive train layouts, when the vehicle is used according to a given driving schedule.

The fuel consumption is estimated with a simulation that was implemented using the mathematical programme Mathematica® Version 3.0 [Wolfram Research 1988-1996]. The simulation procedure is explained in Appendix A.1.

The driving schedule, which is used to determine the fuel consumption, is a bus driving schedule further referred to as the dutch bus driving schedule (DBDS) (**Fig. 5.2**).

The design parameters that are used and determined from being able to perform according to the dutch bus driving schedule are listed in **Tab. 5.1**. It can be seen that in this analysis many parameters are assumed constant except for the ones that were modelled in the previous section. Here the modelled components are the induction motor and the sealed lead acid battery. The parameters that are modelled for the two components are the mass and in case of the induction motor the efficiency was modelled.

Table 5.1: Main design parameters of hybrid bus

Parameter	**Value**	**Unit**
Chassis, Load and Components Mass (excl. Battery and Electric Motor)[a]	12400	kg
Frontal Area	6.9	m^2
Coefficient of rolling resistance	0.0136	
Maximum power requirement for performing driving schedule[b]	150	kW
Maximum speed possible with prime mover only	50	km/h
Prime mover power	40	kW
Maximum short term power requirement from battery (is also maximum power that electric motor must supply)	110	kW
Speed that can be maintained in electric mode for time T_{BLT}	25	km/h
Time (T_{BLT}) over which long term electric power is required	30	min.
Long term power supplied by battery	12.5	kW
Prime mover efficiency		
High-speed gas turbine with heat exchanger	34%	
Internal combustion engine (diesel)	38%	
Lowest level for which prime mover efficiency is assumed (from maximum power output)		
High-speed gas turbine with heat exchanger	80%	
Internal combustion engine (diesel)	40%	
High-speed generator efficiency	90%	
Battery energy efficiency	80%	
Regenerative braking efficiency	60%	
Induction motor mass (equation on p. 141 and table on p. 141)	**Eq. (4.61)** **Tab. 4.22**	kg
Induction motor efficiency (2 pole) (equation on p. 145 and table on p. 147)	**Eq. (4.67)** **Tab. 4.24**	
Battery mass (equation on p. 109 and table on p. 113)	**Eq. (4.12)** **Tab. 4.2**	kg

[a]The mass presents a bus with a load of 24 persons at 68 kg.

[b]The actual combined power requirement of the components may be above this value due to satisfying the maximum torque requirements.

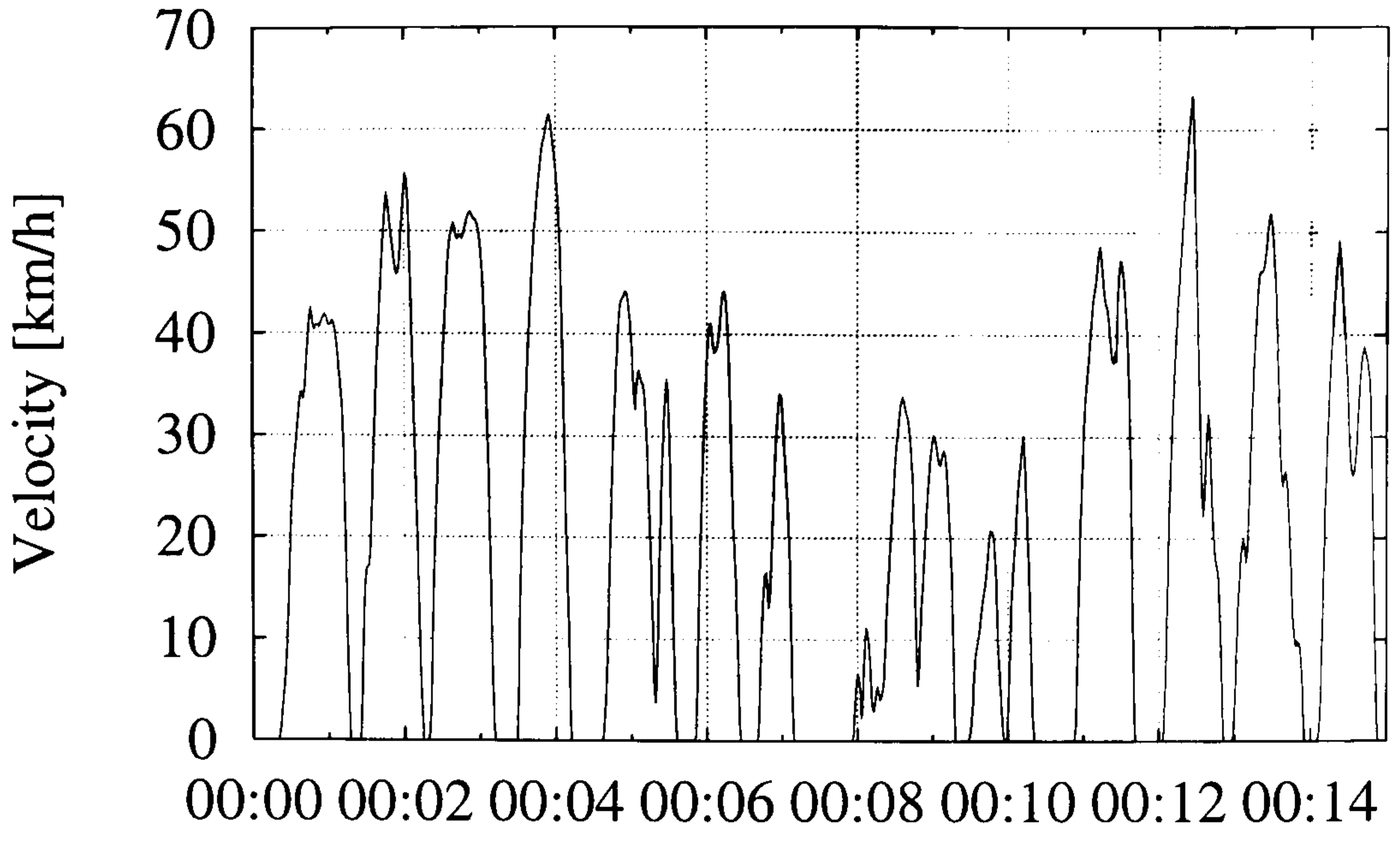


Figure 5.2: Dutch bus driving schedule

5.2.1 Layout Considerations

A relatively small PMU cannot supply the required power needed to accelerate the bus according to the driving schedule. In a hybrid system this is not required from the PMU. The PMU must be able to supply average (or above) energy requirements. The PMU can run at a constant (or near constant) speed near its design point for prolonged periods, thus ensuring optimum operating conditions. A further advantage of the series configuration is the fact that the PMU can run at speed very different to the speed required at the wheel, as there is no mechanical link between the PMU and the wheel. This is in contrast to the parallel configuration.

At times of high power demand the additional power is supplied by the battery and when surplus energy is generated then the battery is there to act as a buffer.

The series configuration is characterised by an additional generator. All the energy is transformed to electric energy and transmitted to either the battery or an electric motor. The losses associated with the transition of *all* mechanical energy to electrical energy is a disadvantage of this configuration.

In the parallel configuration mechanical energy, that is required at the moment of generation, is not converted to electrical energy and back to mechanical energy, as in the series configuration, but goes directly to the wheel. This is the main advantage of the parallel configuration, as it reduces the losses associated with energy conversion.

5.3 Goal, Scope and Procedure

Goal The goal of this study is to estimate the life cycle emissions associated with the use of lead acid batteries and induction motors in a typical parallel hybrid electric vehicle concept (PMU is a Diesel internal combustion engine) and a series hybrid electric vehicle concept (PMU is a gas turbine).

Scope The function of the system is the temporary storage of energy (battery) from the prime mover and from regenerative breaking, the conversion of mechanical energy to electrical energy (electric motor 'generator function' and high speed generator)[1] and the conversion of electrical energy to mechanical energy (electric motor 'motor function').

The life cycle phases included are the pre-manufacturing phases, the manufacturing phases (energy requirements and its associated emissions), the use-phase's energy requirements and emissions, and the transportation associated with recycling the batteries. The first order in the vertical structures of the systems are included (level of detail). The spacial scale of the LCA is the UK (vehicle use, battery recycling), the USA (battery manufacture) and Sweden (electric motor manufacture) and the temporal scale is between 1995 and 2000. The transportation between the different phases is neglected.

An estimate of the accuracy of the results cannot be given, since the models utilised for determining the LCI are estimates of what is practically possible nowadays and don't refer to a specific product.

Procedure The fuel consumption of the vehicle is estimated by the simulation programme, which then can be attributed to the component's mass and efficiency . Furthermore the sizing of the components (battery and electric motor) is based on set design parameters and determined design parameters (from the driving schedule), such as maximum torque, energy and power requirements.

The component's inventory is determined from the models introduced in the previous parts of this thesis, from the relative material composition, from the relative manufacturing inventory and from the relative recycling inventory (in case of the batteries).

The untreated waste streams are determined using The Boustead Model [2000]. An impact assessment was not carried out as it is not required for the demonstration of the method described in this thesis.

[1] Electric motor generator function in the parallel hybrid, electric motor generator function for regenerative breaking and high speed generator function in the series configuration.

Furthermore, it should be noted that the diesel engine and gas turbine relative emission figures, used to determine the untreated waste streams, were gathered from literature. The demonstration of the link between design parameters and emissions is the main intent of this chapter. Therefore the PMU emissions were not rigourously checked and require more analysis for the different types of application[2]. A complete estimative study should ideally include inventory models of all the parts of the drive train (PMU, high speed generator, gearbox).

5.4 Life cycle inventory of modelled components

The motor and battery are the only components that were analysed using the life cycle parameters. The results for the base configurations (see **Tab. 5.1**) are looked at here.

The bus is assumed to run 600,000 km. Over this distance the batteries have to be exchanged several times, but the electric motor is assumed to last for the whole period.

From analysing the state of charge of the battery, as it changes during the driving schedule, together with the cycle life estimates given in **Tab. 4.5** (p. 114) the battery life was estimated. It is estimated that the battery will last for between 11,000 and 12,000[3] driving schedules, with each driving schedule covering a distance of 5.24 km this means a battery life of about 57,000 km to 62,000 km.

5.4.1 Series Configuration

In the simulation programme the DP's for the battery and the electric motor where determined. Over a one minute period[4] the battery has to supply a power of 110 kW[5]. Also the battery must supply power over 30 minutes [4] of 13 kW [6]. Using these constraints the minimum mass of the advanced lead acid battery is estimated as 347 kg according to **Eq. (4.12)** on p. 109 with values from **Tab. 4.2** on p. 113.

The DP's maximum torque for one electric motor was determined as 183 Nm, assuming that the maximum electric motor speed is 6000 rpm. From **Eq. (4.61)** with

[2]E.g. the waste emissions of a small diesel engine for a passenger car are quoted in g/km, while for large diesel engines they are quoted in g/kWh output. Here the later was used (due to problems associated with the units of the small diesel engines), even though the diesel engine of the hybrid is a small engine, such as in a car.

[3]The state of charge (SoC) reaches about 8 times per 30 driving schedules a low peak at 55% in the parallel mode and 65% for the series mode. This was found to give the lowest cycle life.

[4]This parameter was set

[5]Determined from the maximum power requirement of the drive cycle minus the power, that the PMU can deliver

[6]Determined from the requirement of the vehicle to drive in an all electric mode at the average power requirement of the bus at 25 km/h (typical average urban speed).

values from **Tab. 4.22** on p. 141 this means that one motor will have a mass of 142 kg. The maximum efficiency is estimated as 95.3% from **Eq. (4.67)** on p. 145 with values from **Tab. 4.24** on p. 147 assuming a two pole motor design.

The fuel consumption was determined as 40.4 l/100km, which can be attributed in part to the modelled components as is shown in Section 5.8 (p. 178).

Therefore the series configuration requires the following in simplified terms:

- 347 kg of Battery per set of batteries (battery is estimated to last an average of 60,000 km, therefore 10 sets are required over the life cycle of the bus)
- 284 kg of Induction Motor (2 Motors)
- a total of 40 l/100km of diesel fuel

As is illustrated in Section 4.2.6 (p. 115) and Section 4.3.6 (p. 150) the life cycle inventory is simply modelled as being proportional to product mass.

In **Tab. 4.13** (p. 121) an approximate relative material composition of a generic high performance lead acid battery is listed. From this the 347 kg of battery are estimated to result in the use of the materials listed in **Tab. 5.2**. Similarly the inventory associated with the 284 kg of induction motor are listed in **Tab. 5.3** using the estimated material composition in **Tab. 4.25** (p. 151).

5.4.2 Parallel Configuration

As was described in the previous section, the simulation programme was used to determine the DP's of the battery and the electric motor. The battery results are identical to the series simulation as the requirements from the battery are the same.

The DP's maximum torque for one electric motor was determined as 267 Nm, assuming that the maximum motor speed is 3000 rpm. From **Eq. (4.61)** with values from **Tab. 4.22** on p. 141 this means that one motor will have a mass of 195 kg. The maximum efficiency is estimated as 96.1% from **Eq. (4.67)** on p. 145 with values from **Tab. 4.24** on p. 147 assuming a two pole motor design.

The fuel consumption was determined as 32.4 l/100km, which can be attributed in part to the modelled components as is shown in Section 5.8 (p. 178).

Therefore the parallel configuration requires the following in simplified terms:

- 347 kg of Battery per set of batteries (battery is estimated to last an average of 60,000 km, therefore 10 sets are required over the life cycle of the bus)
- 390 kg of Induction Motor (2 motors)

Table 5.2: Simplified inventory of the lead acid battery for the hybrid electric bus with a series configured drive-train

Phase	**Material**	**Quantity**	
Pre-Use[a]	Lead[b]	121	kg
	Lead Dioxide[b]	121	kg
	Sulphuric Acid	28	kg
	Water	42	kg
	Polypropylene	21	kg
	Glass Fibre	14	kg
	Electricity	477	kWh
	Gas	3	kWh
Use	Diesel Fuel due to mass [c] [d]	1.0	l/100km
	Diesel Fuel due to Efficiency [c] [d]	5.0	l/100km
Post-Use[e]	Small Truck transport [f]	12	km
	Medium Truck transport[f]	8	km
	Large Truck transport[f]	52	km

[a] Per set of battery

[b] 48% virgin material and 52% recycled material [Pugh & Breeze 1995]

[c] The PMU and high speed generator efficiencies are taken into account.

[d] Taking into account that a proportion of the energy is regenerated, thus not requiring fuel input.

[e] Per set of battery, for recycling lead

[f] In [Robertson *et al.* 1997] it is stated that the nominal capacities for the small, medium and large trucks are 3.6 t, 16 t and 30 t respectively.

Table 5.3: Simplified inventory of the electric motor for the hybrid electric bus with a series configured drive-train

Phase	**Material**	**Quantity**	
Pre-Use	Copper	23	kg
	Grey Cast Iron	99	kg
	Dynamo Sheer Iron	114	kg
	Steel	28	kg
	Other (Steel, Plastics)	20	kg
	District Heating	132	kWh
	Electricity	712	kWh
	Gas	34	kWh
Use	Diesel Fuel due to mass [a] [b]	0.8	l/100km
	Diesel Fuel due to Efficiency [a] [b]	1.7	l/100km
Post-Use	nd[c]	nd	

[a] The PMU and high speed generator efficiencies are taken into account.

[b] Taking into account that a proportion of the energy is regenerated, thus not requiring fuel input.

[c] no data

- a total of 32 l/100km of diesel fuel

As explained for the series configuration, the life cycle inventory is modelled as being proportional to the product mass.

In **Tab. 4.13** (p. 121) an estimative relative material composition of a generic high performance lead acid battery is listed. From this the 347 kg of battery are estimated to result in the use of the materials listed in **Tab. 5.4**. Similarly the inventory associated with the 390 kg of induction motor are listed in **Tab. 5.5** using the estimated material composition in **Tab. 4.25** (p. 151).

Table 5.4: Simplified inventory of the lead acid battery for the hybrid electric bus with a parallel configured drive-train

Phase	**Material**	**Quantity**	
Pre-Use[a]	Lead[b]	121	kg
	Lead Dioxide[b]	121	kg
	Sulphuric Acid	28	kg
	Water	42	kg
	Polypropylene	21	kg
	Glass Fibre	14	kg
	Electricity	477	kWh
	Gas	3	kWh
Use	Diesel Fuel due to mass [c] [d]	1.0	l/100km
	Diesel Fuel due to Efficiency [c] [d]	3.5	l/100km
Post-Use[e]	Small Truck transport [f]	12	km
	Medium Truck transport[f]	8	km
	Large Truck transport[f]	52	km

[a] Per set of battery
[b] 48% virgin material and 52% recycled material [Pugh & Breeze 1995]
[c] The PMU efficiency is taken into account.
[d] Taking into account that a proportion of the energy is regenerated, thus not requiring fuel input.
[e] Per set of battery, for recycling lead
[f] In [Robertson *et al.* 1997] it is stated that the nominal capacities for the small, medium and large trucks are 3.6 t, 16 t and 30 t respectively.

In **Tab. 5.2** to **Tab. 5.5** it can be seen that the components are assigned a fuel consumption due to their mass. The values listed here are determined from the simulation, and when comparing these values to the figures determined in a simple

Table 5.5: Simplified inventory of the electric motor for the hybrid electric bus with a parallel configured drive-train

Phase	**Material**	**Quantity**	
Pre-Use	Copper	31	kg
	Grey Cast Iron	137	kg
	Dynamo Sheer Iron	156	kg
	Steel	39	kg
	Other (Steel, Plastics)	27	kg
	District Heating	181	kWh
	Electricity	977	kWh
	Gas	47	kWh
Use	Diesel Fuel due to mass [a] [b]	1.1	l/100km
	Diesel Fuel due to Efficiency [a] [b]	1.4	l/100km
Post-Use	nd[c]	nd	

[a] The PMU efficiency is taken into account.
[b] Taking into account that a proportion of the energy is regenerated, thus not requiring fuel input.
[c] no data

way as is shown in Appendix C [7], then it can be found that the values lie within about $\pm 10\%$.

5.5 Untreated Waste Streams of Modelled Components

Entering the inventory from the previous section into The Boustead Model [2000], a life cycle inventory calculations programme, the quantities of the most important chemicals, that are associated with the two concepts, can be estimated. All components are assumed to perform according to the best standard achievable today. For some materials the Boustead Database did not list data and therefore they were substituted with similar materials. Lead dioxide was substituted by lead, dynamo sheer iron by general steel products and grey cast iron by blast furnace pig iron. This procedure of data substitution is common practice in LCA studies and further highlights that the values are estimates.

[7] Here with $\mu = 0.0136$ then the energy energy requirement due to overcoming the rolling resistance is 133 J/(kg km), the energy for overcoming inertia is 263 J/(kg km) for the Dutch Bus Driving Schedule, regenerative braking efficiency is 60%, lower heating value of fuel is 42.1 MJ/kg, fuel density is 0.83 kg/l, average drive train efficiency (from PMU to wheel taking into account that part of the energy passes through the battery) for the series HEV is 26% and for the parallel HEV is 32%.

The PMU of the parallel configuration is a diesel engine. Therefore the emissions from the diesel engine can be estimated from data supplied by diesel engine manufacturers (e.g. [Scania 1999*b*]). Furthermore the emission limit for diesel engines is regulated by the Euro 3 emission standard [Eur 1999, Scania 1999*a*], giving a guide line below which the emissions must lie.

For the series configuration the emissions of the gas turbine are estimated from [Wang 1999*a*, Wang 1999*b*]. It can be seen that most emissions associated with the gas turbine are lower than those for the diesel engine.

In **Tab. 5.6** the emissions, that are used for this demonstration, are listed.

Table 5.6: EU regulations on emissions (Euro 3) and advanced diesel engine emissions

	Euro 3 (2000) [Eur 1999]		**Advanced IC Diesel Engine** [Scania 1999*b*]	[Mikkonen 2000]	**Gas Turbine** [Wang 1999*b*]
	ESC[a]	ETC[b]	ESC[c]	LBC[d]	
Emission	[g/kWh][e]		[g/MJ][f]		
CO	2.10	5.45	0.062	0.108	0.008
HC	0.66	0.78	0.034	0.048	0.002
NO_x	5.00	5.00	0.537	0.757	0.125
PM	0.10	0.16	0.010	0.014	0.014
SO_x[g]	-	-	0.017	0.017	0.017

[a] European steady state cycle for diesel engines
[b] European transient cycle for for gas-powered engines and diesel engines with advanced after treatment
[c] Under steady state conditions the engine is 40% efficient (derived from [Scania 1999*b*]).
[d] A typical London Bus Cycle
[e] Per kWh output
[f] Per MJ of fuel input. Comparison to the Euro Standard is done, by dividing g/MJ value by the engine efficiency and converting from MJ to kWh, e.g. the NO_x-value for the Scania engine is 0.537 g/MJ of fuel used which is $0.537/0.4 \times 3.6$ g/kWh=4.83 g/kWh output, which is below the Euro 3 standard.
[g] The SO_x values are estimated from a fuel sulphur content of 0.38 g/kg (gram per kilogram of fuel), which would produce 0.76 g/kg of SO_2, or 0.018 g/MJ of fuel used.

The bus engine reported by Mikkonen [2000] and Eastlake [2000] emits about 30% higher NO_x-emissions than is allowed by the Euro 3 regulation. This is due to the age of the engine; it was manufactured when the Euro 2 requirements (NO_x-emissions below 7.00 g/kWh) were in effect.

The emission data reported in [Mikkonen 2000, Eastlake 2000] and [Wang 1999*b*] are used for the internal combustion engine and gas turbine respectively in the inventory analysis. The emission data from Mikkonen [2000] is used, as opposed to the Scania [1999*b*] data, as the emission data from Mikkonen [2000] is determined under operating conditions that are more realistic in this context (a typical London bus cycle).

A weak point of the inventory analysis is the size of the PMUs, for which the emission data was determined: the gas turbine data is for a 'controlled gas turbine' using diesel fuel from 1999 (but otherwise unspecified) and the internal combustion engine data is for a large diesel engine, while the diesel engine in the bus is a small engine running at optimum condition. Therefore for the data to represent the simulated situation, the large diesel engine running at varying speeds off its design point must have similar emissions a small diesel engine running at its optimum point. This assumption may not be valid, but up-to-date data for the actual components could not be obtained during this project. It is further seen as not vital to represent exact emission data, as this chapter illustrates a method of implementing the models into the design process.

Entering the inventory data of the electric motor and the battery for the two concepts and the emission data of the the gas turbine and diesel engine into The Boustead Model [2000], gross energy requirements and total untreated waste streams were estimated. The results are shown in **Tab. 5.7** showing the gross energy requirement, in **Tab. 5.8**, where the emissions associated with each component and each life cycle stage is shown and in **Tab. 5.9** the emissions are listed for each life cycle stage.

Table 5.7: Gross Energy Requirement (GER)

Component	**Phase**	**GER [GJ] Ser.**	**Par.**
Electric Motor	Total	639	645
	Pre-Use	15	20
	Use	625	625
Battery	Total	1663	1285
	Pre-Use	134	134
	Use	1508	1130
	Post-Use	21	21
	Total	2303	1929

Phase	**GER [GJ] Ser.**	**Par.**
Pre-Use	149	154
Use	2133	1754
Post-Use	21	21
Total	2303	1929

Table 5.8: Life Cycle Emissions associated with the use of SLA battery and induction motor in a hybrid electric bus

	Emission:	CO_2 [kg]		CO [kg]		NO_x [kg]	
	Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Component	**Phase**						
Electric Motor	Total	47615	47844	13	72	96	455
	Pre-Use	615	844	6	8	2	3
	Use	47000	47000	8	64	94	452
Battery	Total	122500	97500	249	346	285	874
	Pre-Use	11000	11000	218	218	41	41
	Use	110000	85000	19	116	228	817
	Post-Use	1500	1500	12	12	16	16
All	**Total**	170115	145344	262	418	381	1329

	Emission:	SO_x [kg]		CFC [g]		VOC [g]	
	Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Component	**Phase**						
Electric Motor	Total	68	72	0	0	0	0
	Pre-Use	11	15	0	0	0	0
	Use	57	57	0	0	0	0
Battery	Total	231	197	0	0	77	77
	Pre-Use	89	89	0	0	77	77
	Use	137	103	0	0	0	0
	Post-Use	5	5	0	0	0	0
All	**Total**	299	269	0	0	77	77

	Emission:	Pb [g]		Dust [kg]		P [g]	
	Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Component	**Phase**						
Electric Motor	Total	34	47	12	13	0	0
	Pre-Use	34	47	2	3	0	0
	Use	0	0	10	10	0	0
Battery	Total	100	100	64	57	3	3
	Pre-Use	100	100	38	38	3	3
	Use	0	0	25	18	0	0
	Post-Use	0	0	1	1	0	0
All	**Total**	134	147	76	70	3	3

Table 5.9: Life Cycle Emissions associated with the use of SLA battery and induction motor in a hybrid electric bus summarised by life cycle phase.

Emission:	CO_2 [kg]		CO [kg]		NO_x [kg]	
Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Phase						
Pre-Use	11615	11844	224	226	43	44
Use	157000	132000	27	180	322	1269
Post-Use	1500	1500	12	12	16	16
Total	170115	145344	262	418	381	1329

Emission:	SO_x [kg]		CFC [g]		VOC [g]	
Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Phase						
Pre-Use	100	104	0	0	77	77
Use	194	160	0	0	0	0
Post-Use	5	5	0	0	0	0
Total	299	269	0	0	77	77

Emission:	Pb [g]		**Dust [kg]**[a]		P [g]	
Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Phase						
Pre-Use	134	147	40	41	3	3
Use	0	0	35	28	0	0
Post-Use	0	0	1	1	0	0
Total	134	147	76	70	3	3

[a]Includes Particle Matter in the use phase.

5.6 Environmental Impact Assessment

After listing untreated waste streams as was shown in the previous section, an environmental impact assessment (EIA) is required to draw conclusions from the study. The method that is chosen depends on the preferences of the analyst and on the scope at the outset of the LCA. The results obtained often depends on the EIA method chosen, which means it depends on the normalisation and subjective weighting factors in the EIA. At this point it may only be said that it is considered to not further help to convey the method introduced here. The EIA requires as an input the untreated waste streams. They were listed here and that is the main objective of this method. Therefore it is outside the scope of this thesis to carry out an EIA.

The improvement suggestions are usually based on the EIA. As no EIA is carried out it may only be said that the series configuration's higher fuel consumption and resulting higher CO_2-emission must be weighted against the lower NO_x-emissions, lower CO-emissions compared to the parallel configuration.

5.7 Parametric Study

The strength of modelling the concept according to the method explained previously is, that a simulation takes little time, compared to a detailed simulation. In this case, running through the dutch bus driving schedule four times (representing about 20 km) takes about 5 minutes. This allows for a parametric study, where the effect of the individual parameter on the observed output variables is visualised.

The effect is visualised by seeing the effect of relative change. By this it is meant, if a variable is changed by a specific percentage, then what is the relative change on the predicted output variable (see Appendix B).

5.7.1 Varied Parameters

The parameters that were varied to see the effect are

- Excluding the models for battery and electric motor and keeping their performance constant (electric motor is assumed 95% efficient).
- Efficiencies of
  - the PMU (from 0.2 to 0.4)
  - the high-speed generator (from o.75 to 0.95) (series configuration only)
  - the battery (from 0.5 to 0.95)
  - regenerative braking (from 0 to 1)
- Design Parameters
  - Frontal Area A_v (from 6 m^2 to 9 m^2)
  - Coefficient of rolling resistance μ (from 0.010 to 0.018)
  - Drag coefficient c_D (from 0.5 to 0.85)
  - Chassis mass (from 9500 kg to 13000 kg)
  - Long term battery capacity, by varying the time, T_{BLT}, which determines how long the vehicle should operate solely in electric mode (from 5 minutes to 60 minutes)

5.7.2 Fuel Consumption

According to the simulation programme, the bus with a modern diesel engine[8] requires about 49.5 l/100km of diesel fuel for the driving schedule. This compares well to the same type of bus on typical London bus cycle (49.0 l/100km) [Mikkonen 2000] and is reasonable compared to an actual bus fuel consumption average in a German city of 40.0 l/100km ($\pm$ 1 l/100km) [Fendt 2000], taking into account that the German city bus does not stop as regularly as is simulated in the Dutch bus cycle[9].

Compared to this result (49.5 l/100km) the simulation has shown the following:

- For the series configuration the total fuel consumption is about 40 l/100km, a fuel reduction of about 19%.
- For the parallel configuration the total fuel consumption is about 33 l/100km, a fuel reduction of about 33%.

This illustrates the benefit of hybridising an urban bus. Both configurations show significant reductions in fuel consumption compared to the non hybridised version, assuming the best available technology.

5.7.3 Relative importance of design parameters on fuel consumption

In Appendix B the factor, f, is introduced, which indicates the relative importance of a variable on a dependent variable. In this case the dependent variable is the fuel consumption of the vehicle. In **Tab. 5.10** the f-values are listed.

Including the models for the motor and battery results in a 4% to 11% (average 6%) increase in predicted fuel consumption for both the series and the parallel configuration. This is mainly due to the increase in mass of the components and varied efficiency of the electric motor depending on the load.

5.8 Analysis of energy flows

One aspect of the simulation is the visualisation of the energy flows, showing which components of the drive train require what amount of energy. It is distinct for both systems and generalised conclusions can be drawn from this analysis.

[8] Average of 30% efficiency is assumed; when bus stops, engine is assumed to idle and require 5% of its full power energy requirement.

[9] The German bus stops every 400m (Dutch bus cycle about every 375m), but during off-peak hours only on request, being an important factor for decreasing the average fuel consumption.

Table 5.10: A list of f-values for the hybridised bus

Design Parameter	**f-value**	
	Series	Parallel
PMU efficiency	-2.50 to -5.00	-2.50 to -5.00
HS Generator eff.	-0.95 to -1.21	-
Battery eff.	-1.00 to -1.63	-0.9 to -1.3
Regen. braking eff.	-0.53 to -0.55	-0.52 to -0.62
Frontal Area	0.06 to 0.09	0.02 to 0.13
Coef. of roll. resist.	0.36 to 0.39	0.36 to 0.40
Coef. of aerodyn. drag	0.06 to 0.10	0.02 to 0.06
Chassis mass	0.89 to 0.93	0.91 to 1.05
Long term bat. cap.	0.01 to 0.02	0.01 to 0.03

The energy values in the figures are quoted in diesel equivalent usage per 100 km of travelled distance according to the drive cycle. This was chosen to aid understanding. The large megajoule values can tend to be abstract, as we usually don't convert them (in our mind) to something that we can relate to[10].

The Sankey diagrams are shown in **Fig. 5.3** and **Fig. 5.4**, summarising the results from the simulation.

5.9 Discussion

In this chapter it was shown how the modelled inventory is used to determine an estimate of the emissions associated with the product. Here the untreated waste streams were determined using different programmes and the interface was human. This is very time consuming procedure, but the scope for connecting the models to an inventory database, and further integrating an impact assessment procedure should be appreciated.

5.9.1 Procedure

The best case models of the battery mass (Section 4.2.5.1, p. 109) and the electric motor mass (Section 4.3.5.1, p. 139) and efficiency (Section 4.3.5.2, p. 142) were implemented into the simulation program. The battery mass model used is a ULGPRM, since the mass is determined from the specific energy and specific power relationships for batteries. The electric motor mass model utilised is a LLGPRM, since the minimum mass for given torque is of interest in this case. The electric motor

[10] A lower heating value of Diesel fuel of 42.1 MJ/kg with a density of 0.83 kg/l was used.

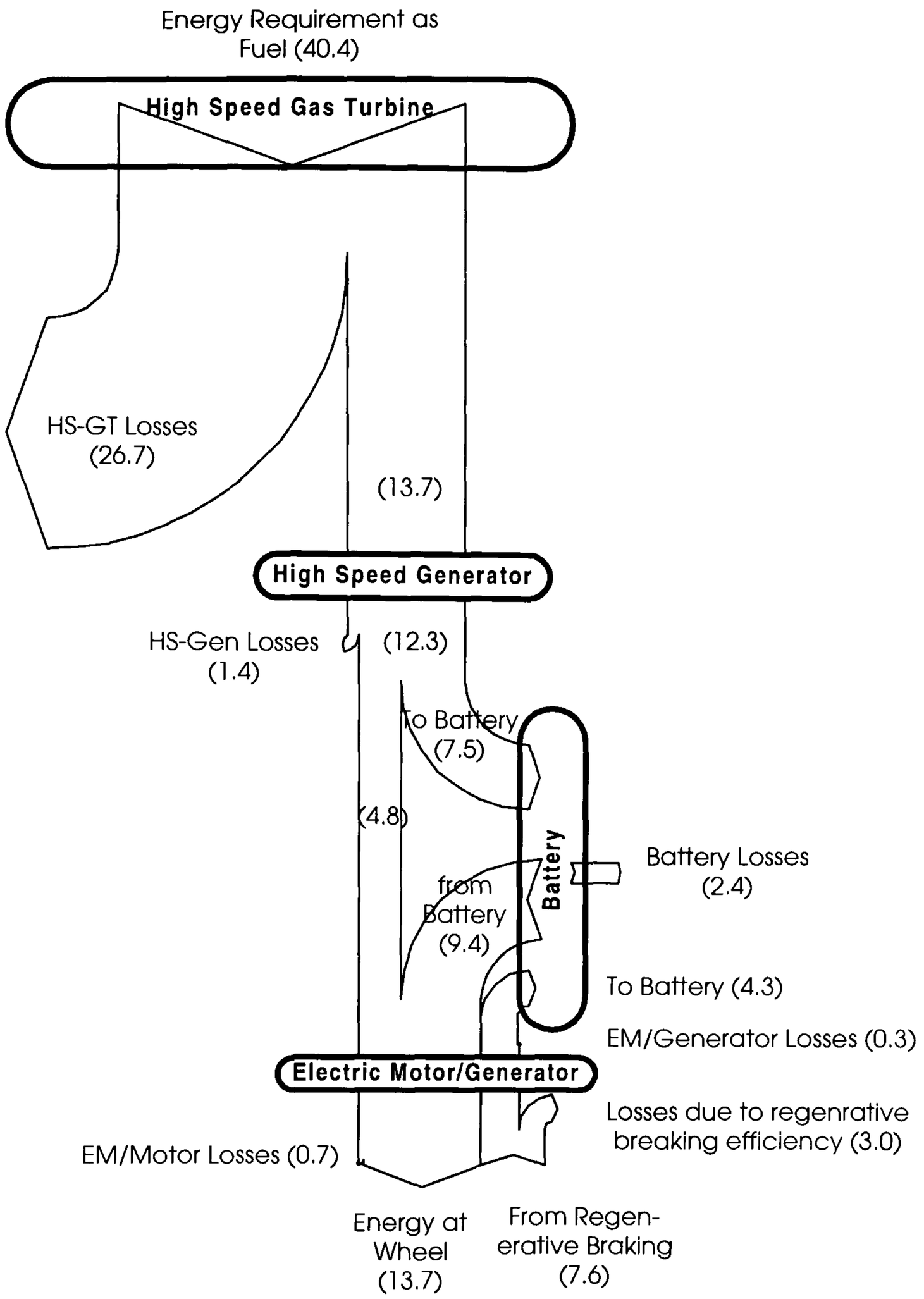


Figure 5.3: Sankey diagram of series configuration (values in litres of diesel fuel per 100 km, density of fuel 830 kg/m^3, lower specific heating value 42.1 MJ/kg)

efficiency model applied in this simulation is a ULGPRM (2-pole), since the maximum efficiency for a given torque was required.

Assumptions The induction motors modelled in Section 4.3 are rib cooled, totally enclosed fan cooled (TEFC) type induction motors. Hybrid vehicles may utilise different methods of cooling on the motor, such as liquid cooling, to further reduce the mass of the motor. Furthermore, the maximum motor speed was assumed a factor 2 higher in the series configuration than the maximum operating speed of the modelled motors, so that this is a further source of error, when determining the minimum motor mass. For the purpose of this study, errors associated with the above are neglected.

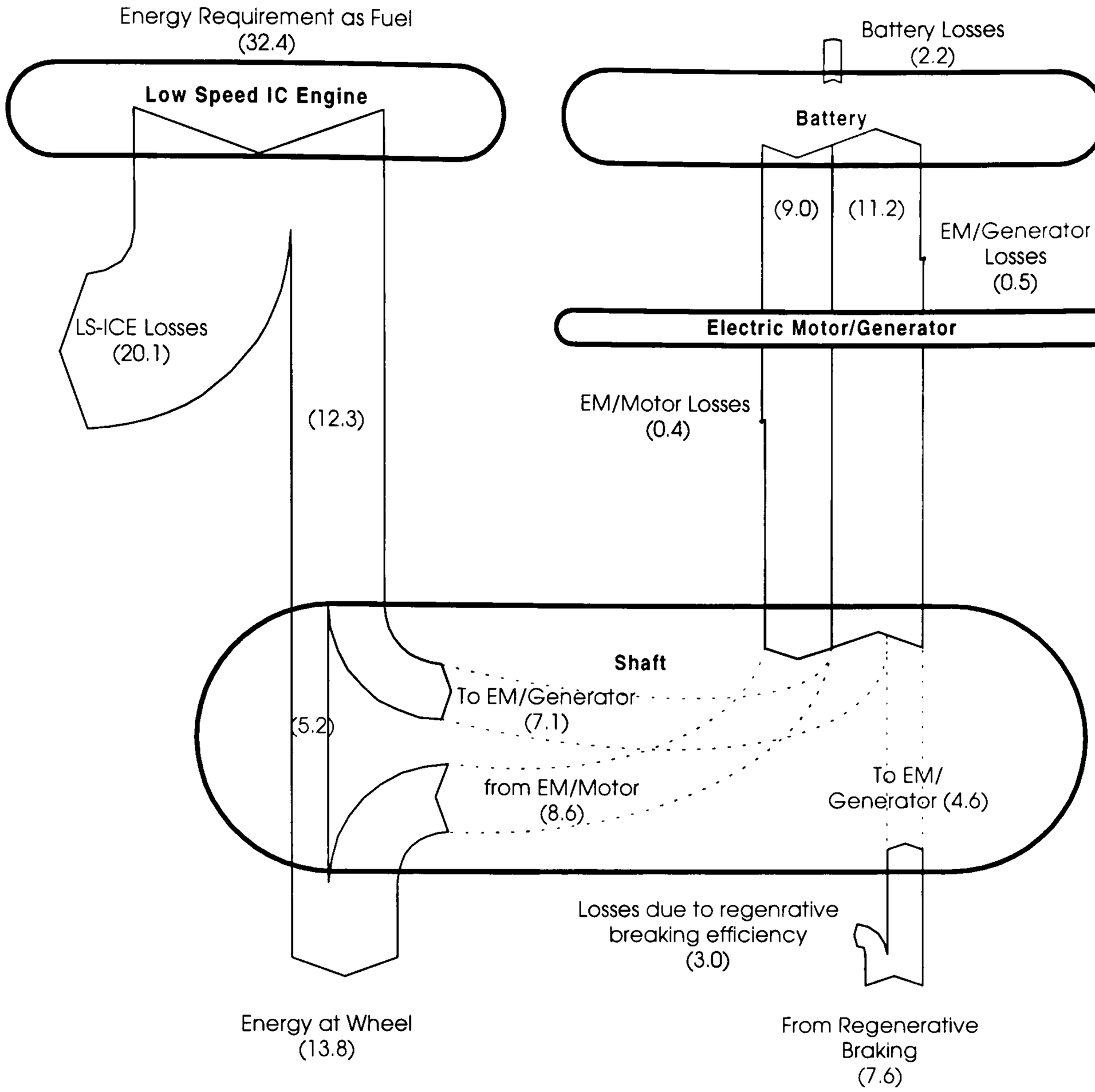


Figure 5.4: Sankey diagram of parallel configuration (values in litres of diesel fuel per 100 km, density of fuel 830 kg/m^3, lower specific heating value 42.1 MJ/kg)

The manufacturers product and production data ideally should have been averaged from several sources, but as mention previously, the required data could not be gathered. In a complete implementation, the inventory models for all the life cycle phases should be estimated from data from various manufacturers. Similarly, the emission data for the internal combustion engine and the gas turbine are from single sources. Comparison of the diesel engines' emission data with the Euro 3 emission regulation indicate the validity of the emission data.

In summary the data used in the hybrid vehicle case study is for the purpose of illustrating how upper and lower limit generic product range models (ULGPRM, LLGPRM) are used to estimate what is 'possible today with the best technology from today'.

Simulation Several components in the simulation of the hybrid vehicle were simplified significantly. The PMUs of the series configuration (small gas turbine) and the parallel configuration (small diesel engine) and the high speed generator of the series configuration where assumed to operate at their maximum efficiency. The effects of varying efficiency is assumed to be negligible for the this study. These effects of varying efficiency can be included, once generic LCP-models (ULGPRM) are developed for the above components. Similarly, the varying efficiency of the battery with load was ignored, due to a lack of an appropriate LCP-model, which in turn could not be established during the course of this project.

The method of the simulation is a *quasi-steady state simulation*. The assumptions are that the driving schedule can be split into a finite number of steps and that for each step the behaviour of all the vehicle components can be assumed constant. This is a limitation, as a real vehicle operates in a continuous manner with transient effects, and small transient changes are not captured by the steady-state steps.

Inventory Analysis The inventory of the components (electric motor and battery) is based on two parts: firstly the pre-use and post-use inventory of the components, which is proportional to the product mass, and secondly the direct and indirect inventory due to the components efficiency (direct) and due to the components mass (indirect), which are linked to the fuel consumption.

The DPs are used within the simulation program to obtain estimates of the LCPs of the electric motor and battery. The LCPs are mass and efficiency (in case of the electric motor). The material composition of the components is approximated via the representative product's inventory. The concept of the representative product was discussed in detail in Section 3.6.1.2 and the application of the concept to the battery and electric motor was shown in Section 4.2.6 and Section 4.3.6 respectively.

The manufacturing and post-use inventory are assumed to be proportional to the mass of the product. The relative manufacturing inventory per unit mass of product output was used. Similarly the post-use inventory is estimated via the inventory per unit mass of used product (in case of the battery). The life of the battery was estimated from the state of charge data. The state of charge data was determined in the simulation programme and this was used to estimate the cycle life of the battery. The cycle life is linked to the driving schedule, so that a service life of the battery could be estimated in terms of distance travelled by the hybrid vehicle.

The maintenance inventory, as part of the use-inventory, is disregarded. The battery and induction motor themselves can be considered maintenance-free, but the maintenance of the vehicle may be proportioned in part to the two products. This is neglected. Further use-inventory is proportional to the associated fuel consumption

of the two products. The direct fuel use, due to the products efficiency, could be determined form the simulation. The indirect fuel use, due to the products' mass. could also be estimated from the influence of the mass on the fuel consumption in the parametric study.

Once the fuel consumptions associated with the products where determined, the emissions (untreated waste streams) where estimated from relative emission values for the PMU. The emissions are listed in terms of mass of emission per fuel energy used.

The inventory data for the different product life phases where entered into the Boustead Database, and thus the emissions and primary energy values could be determined for the different components and for the different life cycle stages.

5.9.2 Results

The results obtained include the waste stream associated with the different components (battery and electric motor) and the various life cycle stages (pre-use, use, post-use). Furthermore, overall fuel consumption estimates and the importance of some design parameters on the overall fuel consumption were analysed.

It has to be taken into account that this is a concept evaluation, which means, that the concept's design parameters are estimated, which leads to an estimation of life cycle parameters (with all the implications discussed in the previous chapters). With the use of average inventory and waste stream data, the results must be viewed in this context.

5.9.2.1 Energy Flow between Components

The discussion refers to the results in **Fig. 5.3** (p. 180) and **Fig. 5.4** (p. 181).

Overall Fuel Consumption and Prime Mover Unit (PMU) The main difference between the total fuel consumption for the series and parallel configuration is due to the higher efficiency of the low speed IC engine. The difference of the PMU efficiencies is 4% and results in a 7% increase of fuel consumption (if the series configuration had a 38% efficient PMU then the fuel consumption would be ca. 37.6 l/100km instead of 40.4 l/100km).

The other main source for the different fuel consumption are the high speed generator losses, which are about 4.0 l/100km of diesel fuel used. The remaining difference comes from the properties of the low speed IC engine running over a wider load range and thus supplying a larger amount of energy to the wheel directly (see below). On the other hand, the larger mass of the electric motor (parallel configuration) incurs

a slight increase in fuel consumption, while the larger electric motor in the parallel configuration has a slightly higher efficiency, resulting in a slight decrease.

The overall drive train efficiency, taking into account regenerative breaking and the losses of the components, is 34% for the series configuration (13.7/40.4) and 43% for the parallel configuration (13.8/32.4).

High Speed Generator As can be seen in **Fig. 5.3** the 1.4 l/100km are lost from the PMU output energy of 13.7 l/100km (10% loss, as shown in **Tab. 5.1**). With the efficiency of the PMU being assumed as 34% this means that the generator alone requires 4.0 l/100km supplied as diesel fuel.

The parallel configuration does not require the additional generator unit and the PMU has a higher efficiency, therefore it requires less primary energy, even though the overall mass of the vehicle is slightly higher.

Battery The battery has three main functions in the hybrid vehicle: firstly to act as a buffer for the energy that the PMU is providing, but for which there is no immediate use, secondly to store the energy from regenerative breaking and thirdly to supply energy, that cannot be supplied by the PMU within the time required (short term power).

The losses of the battery are minimised if the battery efficiency is increased, but also if the buffering function is minimised, i.e. if the energy that the PMU supplies directly to the wheel can be maximised. This is achieved by having a PMU where the performance (in this case only the efficiency, emissions are neglected) is at its optimum over a wider range. The diesel engine was assumed to being able to run between 40% and 100% of its maximum load under optimum conditions, while the gas turbine's optimum conditions where achieved in the range from 80% to 100% of the full load (**Tab. 5.1**). Referring to **Fig. 5.3** (p. 180) and **Fig. 5.4** (p. 181): In the series configuration about 61%[11] of the energy, that comes from the high speed generator, is stored in the battery, while 55%[12] of the energy coming from the electric motor (via the diesel engine, not from regenerative breaking) is stored in the battery in the parallel configuration. This indicates the advantage of the PMU being able to operate efficiently over a wider range since the battery has to buffer less of the energy from the PMU.

[11] From **Fig. 5.3**: 7.5 l/100km 'flow' into the battery from the high speed generator. The total from the high speed generator is 12.3 l/100km. Thus 7.5/12.3=61%.

[12] From **Fig. 5.4**: 7.1 l/100km 'flow' to the battery from the diesel engine, which is reduced to 6.8 l/100km by the low speed electric motor/generator (7.1/(7.1+4.6)×0.5 l/100km=0.3 l/100km; this takes into account that some of the losses are attribute to regenerative breaking.). The total from the diesel engine is 12.3 l/100km.Thus 6.8/12.3=55%.

From the 12.3 l/100km supplied by the PMU, about 42% of the energy (5.2 l/100km) is supplied directly to the wheel, thus avoiding unnecessary losses in the battery (parallel configuration). In case of the series hybrid 39% of the energy from the high speed gas turbine is supplied to the wheel, but some losses occur at the electric motor.

The efficiency losses of the battery are 2.4 l/100km for the series case and 2.2 l/100km for the parallel case. This translates into 5.0 l/100km of fuel required for the PMU in the series configuration and 3.5 l/100km for the parallel configuration, allowing for the efficiency of the PMU and generator and taking into account that some losses can be attributed to the energy recovered from regenerative breaking, for which no fuel was required.

Regenerative Breaking The advantage of hybridising the bus is clearly shown by the energy regenerated from braking. In both cases the potential is 7.6 l/100km but an assumed 60% regenerative braking efficiency reduces this value to 4.6 l/100km. With the low speed electric motors efficiency reducing this value to 4.3 l/100km, which is fed into the battery. When the energy is required again at the wheel about 3.4 l/100km are available from the potential 7.6 l/100km (overall regenerative efficiency is 45%).

Another view is the fuel saved by hybridising in terms of fuel required otherwise to be supplied to the PMU: the 3.4 l/100km would have resulted in about 10.9 l/100km of fuel supplied in case of the parallel configuration and 13.5 l/100km of fuel for the series configuration assuming that the same proportion of energy flows via the battery as in this simulation[13]. Using the simulation programme with the regenerative braking coefficient set to zero, the fuel consumption of the parallel configuration is predicted to increase by 11.5 l/100km and for the series configuration by 13.1 l/100km. The slight difference (±5%) is due to the fact that the proportions of energy flowing through the battery changes as regenerative breaking coefficient changes (e.g. due to the PMU having to run for longer times to recharge the battery, that otherwise would be done by regenerative breaking) and the varying electric motor efficiency is taken into account.

Electric Motor The efficiency losses of the electric motor are two fold: firstly when it is used as a motor and secondly when it is used as a generator.

The electric motor 'motor losses' are 0.4 l/100km for the parallel configuration and 0.7 l/100km for the series configuration. The large difference is mainly due to the parallel configuration not utilising the electric motor as a motor as much as the series configuration, as it supplies a significant amount of energy directly to the wheel.

[13] In the parallel configuration 7.1 l/100km of the 12.3 l/100km flows via the battery (58%) and in the series configuration 7.5 l/100km of 12.3 l/100km flows via the battery (61%).

The electric motor 'generator losses' are 0.5 l/100km for the parallel hybrid and for the series configuration they are 0.3 l/100km. Here the difference is mainly due to the parallel configuration utilising the electric motor as a generator for part of the energy that is supplied by the PMU, while in the series configuration the energy conversion is performed by the high speed generator.

The total efficiency losses of the electric motor are 1.0 l/100km for the series case and 0.9 l/100km for the parallel case. This translates into 1.7 l/100km of fuel required for the PMU in the series configuration and 1.4 l/100km for the parallel configuration taking into account that some losses can be attributed to the energy recovered from regenerative breaking, for which no fuel was required. These values take into account the proportion of energy flowing via the battery and the proportion supplied directly from the PMU (parallel configuration) or the high speed generator (series configuration).

5.9.2.2 Parametric Study

Referring to **Tab. 5.10** (p. 179) the following was found.

The design parameter, where the smallest relative change will result in the largest fuel saving, is the increase of the prime mover efficiency. If the PMU has a maximum operating efficiency 34% then a 1% increase in efficiency will result in a 3% decrease in fuel consumption.

The second most important factor is the battery efficiency. A 1% increase in the charging/discharging cycle energy efficiency results in about 1% decrease in fuel consumption for both the series and the parallel configuration.

For the series configuration, a 1% increase in the high speed generator efficiency reduces the fuel consumption by ca. 1%.

Another important factor is the vehicle mass. A 5% reduction in mass will result in about a 4% reduction in fuel consumption.

The regenerative breaking coefficient represents how much energy can be 'won back' from the driving schedule. If this coefficient can be increased by 5% then the fuel consumption is reduced by about 2.5% for the series configuration and 3% for the parallel configuration.

A further important parameter is the coefficient of rolling resistance. A 5% decrease in the coefficient will result in an approximate 2% reduction in fuel consumption.

It has to be mentioned that the reductions in fuel consumptions are not cumulative and that the relative change in fuel consumption will change as the parameters are changed, but they give a valid indication, which parameters have the largest impact on the fuel

consumption. The quantitative estimate of change is of value as it shows how much needs to be done to achieve the specified change in fuel consumption.

5.9.2.3 Untreated Waste Streams (Emissions)

The data for the GER and untreated waste streams was tabulated in **Tab. 5.7** to **Tab. 5.9**. The tables list the data with respect to the components and the life cycle phases and secondly the life cycle phases' data of the components is added to summarise the data for each life cycle phase. The second representation of data is more relevant as more components are analysed.

An environmental impact assessment was not carried out in this study, since it was not considered necessary to illustrate the application of the method. In the following each waste stream is analysed by comparing how important the life cycle phases of the two components are to the particular emissions. The components' most significant life cycle phases with respect to the individual emissions are briefly explained in terms of the design parameters of the components and hybrid vehicles, that affect the waste stream most.

To aid the understanding of the importance of the GER and the emissions on the various life cycle stages and between the two concepts, the GER and emission data is represented as a percentage of the Series Configuration's total values. This relative data is listed in **Tab. 5.11** and **Tab. 5.12** and was derived from **Tab. 5.7** and **Tab. 5.8** respectively.

Table 5.11: Relative Gross Energy Requirement (GER) (Totals of all components of series configuration are used as reference values)

		GER [GJ]	
Component	**Phase**	**Ser.**	**Par.**
Electric Motor	Total	28%	28%
	Pre-Use	1%	1%
	Use	27%	27%
Battery	Total	72%	56%
	Pre-Use	6%	6%
	Use	66%	49%
	Post-Use	1%	1%
All	**Total**	100%	84%

Gross Energy Requirement (GER) and Carbon Dioxide (CO_2) The first observation is that the GER of the parallel configuration is only 84% of the series configuration. In absolute terms, the series configuration's battery and electric motor

Table 5.12: Relative Life Cycle Emissions associated with the use of SLA battery and induction motor in a hybrid electric bus (Totals of all components of series configuration are used as reference values, totals may not agree due to rounding of values)

	Emission:	CO_2		CO		NO_x	
	Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Component	**Phase**						
Electric Motor	Total	28%	28%	5%	27%	25%	119%
	Pre-Use	0%	0%	2%	3%	1%	1%
	Use	28%	28%	3%	24%	25%	119%
Battery	Total	72%	57%	95%	132%	75%	229%
	Pre-Use	6%	6%	83%	83%	11%	11%
	Use	65%	50%	7%	44%	60%	214%
	Post-Use	1%	1%	5%	5%	4%	4%
All	**Total**	100%	85%	100%	159%	100%	349%

	Emission:	SO_x		CFC		VOC	
	Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Component	**Phase**						
Electric Motor	Total	23%	24%	-[a]	-	-	-
	Pre-Use	4%	5%	-	-	-	-
	Use	19%	19%	-	-	-	-
Battery	Total	77%	66%	-	-	100%	100%
	Pre-Use	30%	30%	-	-	100%	100%
	Use	46%	34%	-	-	-	-
	Post-Use	2%	2%	-	-	-	-
All	**Total**	100%	90%	-	-	100%	100%

	Emission:	Pb		**Dust**[b]		P	
	Concept:	**Ser.**	**Par.**	**Ser.**	**Par.**	**Ser.**	**Par.**
Component	**Phase**						
Electric Motor	Total	25%	35%	16%	17%	-	-
	Pre-Use	25%	35%	2%	3%	-	-
	Use	-	-	13%	13%	-	-
Battery	Total	75%	75%	84%	75%	98%	98%
	Pre-Use	75%	75%	50%	50%	98%	98%
	Use	-	-	33%	24%	-	-
	Post-Use	-	-	2%	2%	-	-
All	**Total**	100%	110%	100%	92%	100%	101%

[a] "-" means that absolute value is <0.5 units in **Tab. 5.8** and therefore where rounded to zero.

[b] Includes Particle Matter in the use phase.

require 2.3 TJ over their entire life cycle, while the parallel configuration's require 1.9 TJ (**Tab. 5.11**, p. 187). The largest part of the difference arises from the use phase of the battery. The parallel configuration's battery requires about 25% less gross energy during the use phase compared to the series configuration battery. This has two reasons: firstly the PMU generator combination of the parallel configuration is more efficient (accounts for about 15% of the 25%) and secondly the battery is not as heavily used in the parallel configuration as was shown in Section 5.9.2.1 (accounts for about 10%).

The CO_2-emissions are directly related to the GER, since the largest part of the GER is accounted by the use of fossil fuel during the use phase. Consequentially the relative values of the CO_2-emissions are similar to the relative GER values, and the previous paragraph's reasoning applies .

Carbon Monoxide (CO) The total values of the CO-emissions are about 60% higher for the parallel configuration, which directly relates to the significantly lower emissions of the gas turbine with respect to this emission. The series and parallel configuration have similar amounts of CO-emissions associated with the pre-use and post-use phases of the battery and electric motor.

It is noticeable though, that a significant part of the CO occurs in the pre-use phase of the battery. Almost all (98%) of the battery's pre-use CO-emissions occur during the making of the lead. In order to decrease the emission over the entire life cycle, the CO can be reduced during the use phase of the hybrid vehicle and by utilising less primary lead.

The reduction during the use phase — especially for the parallel configuration — can be achieved by reducing the overall fuel consumption, by an improved combustion process or by exhaust gas after treatment. The reduction of primary lead in the battery can be achieved by extending the battery life, by increasing the recycling fraction and by using alternative battery technology.

Nitrogen Oxides (NO_x) The NO_x-emissions are a factor of 3.5 times higher for the parallel configuration. The largest part of the NO_x-emissions occur in the use phase of the battery and electric motor. This is due to the diesel engine's combustion process, which emits significantly larger amounts of NO_x compared to the gas turbine.

As with the previous emission, the reduction of NO_x during the use phase — especially for the parallel configuration — can be achieved by reducing the overall fuel consumption, by an improved combustion process and by exhaust gas after treatment.

Sulphur Oxides (SO_x) The relative SO_x-emissions where assumed equal for the gas turbine and for the diesel engine, as it was assumed that they use the same fuel. Since the parallel configuration requires less fuel, the use phase SO_x-emissions are lower for the battery compared to the series configuration. The parallel configuration's electric motors are larger and therefore a higher indirect fuel consumption is associated with their mass, but the overall more efficient PMU generator combination results in a lower fuel requirement due to the efficiency losses of the electric motor. This coincidentally results in the fuel requirement associated with the electric motor being equal for the use phase of the electric motor for the series and parallel configurations.

A significant percentage of SO_x is associated with the pre-use phase of the battery. As with the CO-emissions, SO_x-emissions of the pre-use phase of the battery are largely associated with the use of lead. In order to decrease the emission over the entire life cycle, the SO_x can be reduced during the use phase of the hybrid vehicle and by utilising less primary lead by the same means as mentioned for the CO-emissions.

Lead (Pb) The Pb-emissions occur mostly in the pre-use phase of the electric motor and battery. It is associated with fuel use and process operations during the processing of the raw materials and the manufacture of the components. The most important source is the lead production. Therefore the Pb-emissions can be reduced by utilising less primary material.

Dust The largest part of the dust emissions are spread between the pre-use phase and the use phase of the battery. The parallel and series configuration emit similar levels of dust, as the mass of the battery is equal for both configurations and the relative dust emissions for the gas turbine and the internal combustion engine were equal.

Other emissions Chlorofluorocarbon compounds (CFC), Volatile organic compounds (VOC) and Phosphorous compounds (P) are negligible in this context as the absolute values are extremely low.

5.9.3 Summary

The results from the parametric study have illustrated that in order to reduce the overall fuel consumption (for both the series and parallel configuration) the PMU efficiency is of primary importance, but the battery efficiency, high speed generator efficiency (series configuration only), gross vehicle mass, the proportion of regenerated energy and rolling resistance are also of significant importance. Depending further on, which of these parameters the designer can improve most effectively, these are areas.

which a designer should consider first, when designing and selecting components of a hybridised bus, with the minimisation of the overall fuel consumption as an aim.

The energy analysis of the components have highlighted the strength and weakness of the concept itself and of its components. The parallel configuration's main strength is that a significant part of the energy can be supplied to the wheel, without being converted from mechanical to electrical and back to mechanical energy again, thus avoiding the associated conversion losses.

The strengths of a PMU (here the diesel engine), which can supply power over a relatively large power range at or near its peak efficiency, were shown to result in a lower utilisation of the battery and thus decrease the total battery losses.

The analysis of the emissions has highlighted that the superior conversion efficiency of the diesel engine, compared to the gas turbine, results in a lower GER, CO_2- and SO_x-emissions, but its relatively poor CO- and NO_x-emissions result in these emissions being significantly higher for the use-phase of the battery and motor in the parallel configuration. An environmental impact assessment is required to evaluate the relative importance of the absolute values of the emissions and thus to conclude which concept is preferable with respect to the overall impact.

The material requirements for the battery incur for both configurations significant pre-use CO-, SO_x- and dust-emissions. This emphasises the importance of reducing primary materials in the battery, which can be achieved by extending the battery life, by increasing the recycling fraction or by using alternative battery technology (which requires a similar assessment for comparison).

6 Summary and Conclusions

In the past the engineering community has become increasingly aware of the importance of making correct design decisions as early as possible during the design process. This also applies to whole life cycle considerations. As a result, an engineer requires help in assessing the life cycle of a product throughout the design process, to visualise the effect of design decisions with respect to the entire life cycle and to highlight the significance of design parameters on the whole life cycle. The assessment must be carried out repeatedly during the design process and the time and resources required must be reduced. This is a vital aspect of a practical life cycle assessment (LCA) method which may be utilised in engineering design. Aspects of the engineering design process and life cycle assessment where discussed in Chapter 2. Key requirements for a practical and 'integrated' assessment of the life cycle were identified. Previous approaches to life cycle assessment were discussed and it was found that they are either based on the reduction of data — by omitting life cycle phases, specific inventories or impact assessment — or are aimed at the more detailed embodiment design. Little research has been attempted to develop a framework for integrated, quantitative life cycle assessment during the concept design phase. At this early stage and at this level of detail three factors become important with respect to life cycle assessment:

- the 'fuzzy' definition of the design and the resulting uncertainty of life cycle assessment results,
- the low cost of change and the early focus on key issues of the design with respect to the whole life cycle and
- the visualisation of the influences of concept design decisions on the whole life cycle.

Chapter 3 outlined a methodology for life cycle assessment during concept design, addressing the above factors. The methodology focuses on establishing an approximate life cycle inventory, by relating various design parameters, which can be estimated at the concept stage of the design process, to the individual life cycle phases' inventory.

It was recognised that there are a limited number of parameters that can be directly related to various parts of the life cycle inventory. These 'life cycle parameters' are in part related to design parameters, while others are design parameter independent, but they have in common, that they can be estimated during the early phase of the design process either directly or indirectly, by estimating the related design parameters.

Products and product ranges are analysed in two ways:

- Relationships of life cycle parameters to design parameters are analysed and expressed as relatively simple, often empirical mathematical models. 'Generic product range models' to 'specific product models' are types of models representing a decreasing level of uncertainty.

- Average inventories associated with the individual life cycle phases of the product range are represented in relative terms of life cycle parameters.

The proposed methodology includes guidelines on how to establish the relationships and average inventories and how finally the models and relative inventories are used to estimate the life cycle inventory.

In summary the methodology presents a single framework suitable for estimating the life cycle inventory during the concept evaluation process. It is intended to highlight the key design parameters and the strengths and weaknesses of a concept with respect to the whole life cycle. The novel features of the approach include:

- The approach's practicality in an engineering design environment was considered throughout the development of the framework.

- Definition of life cycle parameters, as parameters that have a direct relationship to part of the inventory. Some life cycle parameters are further related to design parameters, while others are design-parameter-independent.

- Systematic determination and representation of life cycle parameters in terms of design parameter, which can be estimated during the early phase of the design process. This is seen as the main aspect of integrating life cycle assessment into the design process, as it represents a link between what the designer 'knows' and the inventory.

- Types of models are distinguished, representing different levels of uncertainty, as the design moves from the generic to the more specific.

- Average inventories for products and product ranges are analysed and represented relative to life cycle parameters.

- The process of estimating the life cycle inventory and carrying out a life cycle assessment in this context is outlined.

- The approach is suitable to be extended to include monetary evaluation of the life cycle of the design concept.

The two case studies in Chapter 4 are examples of how the inventory models are determined for standard engineering products and they clarify various points raised during the development of the methodology. The products analysed are sealed lead acid batteries and 3-phase asynchronous electric motors. General and some specific points raised include:

- The modelling of life cycle parameters as functions of design parameters for real components has highlighted that theoretical analysis and accepted empirical relationships form a good basis for determining the models. The models required only little modification to suit the actual data evidence.

- The data gathering process, required for establishing the models and for the relative inventories, is time consuming work, but together with the modelling this has to be seen as an 'investment' as it is used to generalise the inventory, which is used for subsequent evaluations. In one case, data required for modelling the life cycle parameters, was obtained from a third party, which considerably reduced the amount of work. Annual business and environmental reports, as issued by larger European companies, is a valuable source of information for the average manufacturing inventory. Annual business reports are common for publicly owned companies and the environmental reports are becoming increasingly popular with the growing awareness and interest of the public.

- The comparison of the different types of models (specific product models, specific product range models, generic product range models) with actual product data has illustrated that the range, within which the predicted values lie, decreases as the models become more specific.

In Chapter 5 the methodology was applied to the evaluation of the battery and the electric motor in the two main drive train concepts of a hybrid electric vehicle (series and parallel configuration). The main reason for this case study was to demonstrate how the developed inventory models may be used to analyse the inventory. It was illustrated how the models ('best case' generic product range models) were integrated into a simulation programme (this would have been impossible using the raw data) and used to estimate the material and energy requirements. These requirements were entered together with relative combustion emissions into a life cycle inventory programme. In this case study the method has proven extremely useful in estimating

the size of the components (according to the best technology available) and the associated material and energy requirements. The results gained from the case study illustrate that the methodology can be used for comparing concepts with respect to their life cycle impacts and for determining those design parameters which have an important influence on the life cycle of the concept.

The potential of the methodology may be fully appreciated once life cycle parameter models and relative inventories of several engineering products are implemented in a user friendly manner (a software programme). In combination with life cycle inventory data on raw materials, engineering materials, energy conversion processes and transportation, the time required for estimating the life cycle inventory and subsequent impact assessment would be greatly reduced. The use of software would not only reduce the amount of time required for an assessment, thus enabling to carry out estimative life cycle assessments in an iterative manner, but it would also aid the handling of sensitivity analysis techniques. Consequently, further work to this thesis would include the determination of life cycle parameter models and relative inventories of several components and products (from various fields, such as mechanical, electrical and civil engineering and even services, such as telecommunication, entertainment and medical) and the embodiment in software.

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A. Hybrid Vehicle Simulation: Further Information

In this chapter information on the hybrid vehicle simulation, that is not directly related to the main point of this thesis, is given.

A.1. The Simulation Procedure

The simulation is implemented using the mathematical programme Mathematica® Version 3.0 [Wolfram Research 1988-1996]. The basic equation that is used is derived from the equation of solid-body motion (Newtons Second Law), which is in its scalar form

$$F = m\,a \tag{A.1}$$

This equation is modified to the forces that typically act on the vehicle, which are the the forces to overcome aerodynamic drag, forces to overcome rolling resistance, the force to overcome the effect of inertia and the potential forces needed to overcome hill climbing. Therefore the equation for the force required at the wheel is [Beitz & Küttner 1990]

$$F = \frac{1}{2}\,\rho\,c_D\,A_v v^2 \;+\; m\,g\,\mu \;+\; m\,a \;+\; m\,g\,sin(\Theta) \tag{A.2}$$

where F is the force at the wheel ρ is the density of air, c_D is the coefficient of aerodynamic drag, A_v is the frontal area of the vehicle, v is the magnitude of the velocity (vehicle speed), m is the mass, g is the acceleration due to gravity, μ is the coefficient of rolling resistance, a is the actual acceleration and Θ is the slope angle of the hill.

The force is acting at the outer perimeter of the wheel with a radius r_w at the linear vehicle speed v. Therefore the rotational speed is $\omega = \frac{v}{r_w}$ and the moment at the wheel is $M = F\,r_w$.

Energy is the sum of forces times the distance s over which the forces act and the sum of moments times the angle θ over which they act,

$$E = \int_{s_1}^{s_2} (\sum F\, ds) + \int_{\theta_1}^{\theta_2} (\sum M\, d\theta) \tag{A.3}$$

For constant forces and moments

$$E = \sum F(s_2 - s_1) + \sum M(\theta_2 - \theta_1) \tag{A.4}$$

With the power P being energy delivered in a time t, $P(t) = \frac{dE}{dt}$ then power per unit time is in scalar form

$$P(t) = \sum F_t\, v \; + \; \sum M_t\, \omega \tag{A.5}$$

With

$$E = \int_{t_1}^{t_2} dE = \int_{t_1}^{t_2} P(t)\, dt = \bar{P}(t_2 - t_1) \tag{A.6}$$

where $\bar{P}$ is the mean power and t is time. Therefore

$$\bar{P} = \int_{t_1}^{t_2} \frac{P(t)dt}{t_2 - t_1} = \frac{E}{t_2 - t_1} \tag{A.7}$$

Eq. (A.6) is the main equation used in this simulation, where $\bar{P}$ is taken from **Eq. (A.2)** and the times t_1 and t_2 are subsequent time steps in the driving schedule. The energies for the different parts are stored in matrixes to allow detailed examination of the energy flows between the components.

This method of simulating the vehicle is a *quasi-steady state simulation*. The assumptions are that the driving schedule can be split into a finite number of steps and that for each step the behaviour of all the vehicle components can be assumed constant. This is a limitation, as a real vehicle operates in a continuous manner with transient effects, and small transient changes are not captured by the steady-state steps.

In **Eq. (A.2)** it is illustrated that the mass of the components play an important role. At this moment only the three-phase electric motor and the batteries are included and the mass of the other parts are taken to be constant. Furthermore only the efficiency of the three-phase electric motor is modelled and other efficiencies are assumed constant.

Nevertheless, this illustrates the power of the models as it allows an efficient way to represent the data and thus to perform the simulation efficiently. The strength of this method will become more apparent as more models are developed and included. The efficient method of representing the parameters allows the performance of parametric studies where a large number of runs are performed and only changing one parameter at a time.

A.1.1. Initialisation an Component Sizing

First some design parameters are set in order to determine the design parameters listed in **Tab. 5.1**. The set parameters are

- Chassis and Components Mass (excl. Battery and Electric Motor), m
- Frontal Area, A_v
- Coefficient of aerodynamic drag c_D
- Coefficient of rolling resistance, μ
- Maximum speed possible with prime mover only, v_{PMU}
- Speed that can be maintained in electric mode for time T_{BLT}, v_{El}
- Time over which long term electric power is required, T_{BLT}
- Prime mover efficiency, η_{PMU}
- High-speed generator efficiency, η_{HSGen}
- Battery energy efficiency, η_{Bat}
- Regenerative braking efficiency, η_{RB}

After setting these parameters the driving schedule is used to determine further parameters in an initial sizing run. The parameters that are determined from the requirement of being able to perform according to the dutch bus driving schedule in **Fig. 5.2** are the the following

- Maximum power requirement, P_{max}
- Prime mover power, P_{PMU}
- Maximum short term power requirement from battery, P_{BatST}
- Maximum power that the electric motor must supply, $P_{El} = P_{BatST}$
- Long term power supplied by battery, P_{BatLT}
- Lowest level for which prime mover efficiency is assumed, $k_{\eta PMU}$, which means that the prime mover is only operated between this lowest level and 100% of its power capability

The life cycle parameters that are modelled in Section 4 are used and determined using the relevant design parameters

- Induction motor mass, m_{ElM}, (**Eq. (4.61)** and **Tab. 4.22** on p. 141, LLGPRM)
- Induction motor efficiency (2 pole), η_{ElM}, (**Eq. (4.67)** on p. 145 and **Tab. 4.24** on p. 147, ULGPRM)
- Battery mass, m_{Bat}, (**Eq. (4.12)** on p. 109 and **Tab. 4.2** on p. 113, ULGPRM)

All the parameters are then fixed for the duration of the simulation.

A.1.2. Simulating Driving

Once the design parameters are fixed, speed and time data from the driving schedule is taken for simulating driving. The power requirements due to aerodynamic drag and overcoming inertia and rolling resistance is determined from the design parameters and driving schedule. Instantaneous energy requirements for all the steps of the drive train (see **Fig. 5.1**, p. 164) are updated every second of the driving cycle and thus the primary energy demand is determined. Furthermore the procedure is set up to determine the losses at all the steps and to record the inputs into each step.

A further feature of the simulation is that the state of charge is recorded to make sure that the battery is not overloaded or over-drained. Furthermore this information is useful in the context of how long a battery is expected to last.

The driving schedule is used 4 to 10 times to simulate a longer distance.

A.1.2.1. Controlling the PMU

The prime mover is 'switched on of off' depending on the state of charge (SoC) of the battery and on instantaneous and average power requirements. The rules are

- if the prime mover is off and
  - if the average power demand (over a given period) is above the lowest level at which the prime mover can supply power at the stated prime mover efficiency and the SoC is below the 'upper switch off limit' then the prime mover is switched on
  - if the SoC falls below the 'lower switch off limit' and there is an instantaneous energy demand then the prime mover is switched on
  - if the SoC falls below half the 'lower switch off limit' the prime mover is switched on
- if the prime mover is on and

- if the average power demand (over a given period) is below the lowest level at which the prime mover can supply power at the stated prime mover efficiency and the SoC is above the 'upper switch off limit' then the prime mover is switched off
- if the SoC rises above the 'upper switch off limit' and there is no instantaneous energy demand then the prime mover is switched off
- if the SoC reaches 100% then the prime mover is switched off

It can be seen from this that the PMU does not run continuous, but its speed is varied within a speed range where the PMU can supply the mechanical power at the stated efficiency.

A.1.2.2. Assumptions and Limitations of Simulation

In the following assumptions and limitations of the simplified simulation procedure are listed.

THREE-PHASE ASYNCHRONOUS MOTOR The three phase induction motors, modelled in Section 4.3, are designed to operate at constant speed. The additional power electronics, that are required to control the asynchronous motor for variable speed applications are neglected. Furthermore, the series configuration has the advantage of the electric motor being not mechanically linked to the PMU, so that a higher speed motor can be used. Here it is assumed that the series configuration motor can operate at speeds below 6,000 rpm, while the parallel configuration electric motor can operate at speeds below 3,000 rpm, which is similar to the operating speed of the PMU. This results in the electric motor being considerably smaller for the series configuration and therefore lighter. It is anticipated, that the electric motor's mass will be increased to incorporate additional cooling methods, especially for the assumed high speed induction motor. At this point this is neglected.

BATTERY It is assumed that the battery can supply and store all the energy that is demanded from it or supplied to it irrespective, of its state of charge. In reality there is a limit in how much energy can be stored or supplied per unit time by the battery. It depends on factors such as temperature and state of charge. When initially sizing the battery the maximum short term power demand is determined from the drive cycle and is used to size the battery. Therefore the maximum power that is demanded can be supplied by the battery. The instantaneous energy bursts from the regenerative braking are moderated by assuming an the average regenerative braking efficiency. For the purpose of this estimative study this is sufficient.

Furthermore the battery's state of charge is returned to the same as at the beginning of the simulations, thus making sure that the net energy supplied and received by the battery over the simulated distance is zero.

PRIME MOVER UNIT It is assumed that the prime mover (high speed gas turbine or the internal combustion engine) supply the energy at an average efficiency. Furthermore, the mass of this component is assumed constant, irrespective of its size.

It is anticipated that the neglected change in efficiency depending on the size and the actual load condition has a significant impact on the result, but this simulation has to be seen as what is possible with the technology available.

HIGH SPEED GENERATOR For the purpose of this simulation the high speed gas turbine is assumed to convert the mechanical energy to electrical energy at a constant efficiency. Furthermore, the mass of this component is assumed constant, irrespective of its size.

GEARBOX When determining the maximum torque, that the PMU and the electric motors have to supply, a six-speed gearbox is assumed, with geometrically equally spaced steps between 0 m/s and the maximum speed of the vehicle. The gearbox's efficiency is neglected.

OTHER COMPONENTS Further components, such as bearings and auxiliary devices, are neglected in this simulation.

The assumptions are mainly due to the fact that models were not available for the different components. The inclusion of appropriate LCP-models will improve the overall simulation. The results from the simulation should be seen in the context of highlighting key areas, which need attention when designing the hybrid vehicle. In this respect the results are valid.

A.1.3. Results Output

As was mentioned previously a simulation is completed by creating an output file that lists all the input parameters and results. The results include the sized parameters and energy values for the various stages of the drive train. Furthermore a histogram data is stored on the battery state of charge to give an indication of how much the battery is strained during the drive cycle. In the following the energies are listed that are recorded as an output to the simulation.

- Total primary energy

- Prime mover unit energy
- Energy from high-speed generator
- Energy losses high-speed generator
- Electric motor functioning as a generator losses
- Electric motor functioning as a motor losses
- Battery losses
- Maximum energy (potentially) regenerated from driving schedule
- Energy actually regenerated from driving schedule
- Energy to electric motor functioning as a motor
- Energy from electric motor functioning as a generator
- Minimum energy to driving schedule
- Energy to battery
- Useful energy from battery
- Energy to electric motor functioning as a motor, but not coming from the battery
- Energy from high-speed generator to battery
- Battery state-of-charge histogram data

These results allow an analysis of how the input energy (primary energy) is used to perform the function of moving the vehicle according to the given drive cycle.

A.2. Verification

A.2.1. Comparison with a simple case

A simple case was set up and running the simulation with a very simple driving schedule showed that the result deviates less than 1% from the result obtained manually. The small deviations may be attributed to successive rounding errors.

Table A.1.: Comparison of simulation results with results reported in [Senger 1997]

Case, Source	**Gasoline Fuel Consumption [l/100km]**		**Difference to real [%]**	
	FUDS	FHDS	FUDS	FHDS
Real Vehicle [Senger 1997]	9.5	5.8	-	-
Advisor Simu. [Senger 1997]	10.8	7.2	14	24
This Simulation	9.4	7.5	-1	29

A.2.2. Comparison with published data

The second method was to compare results from this case study to a case study from [Senger 1997]. The design parameters of the series hybrid passenger vehicle were extracted and running the simulation, described here, it was shown that the simulation predicts the fuel consumption to within 30% of the real vehicle, but it has to be mentioned that the real vehicle data was criticised in the aforementioned for being unreliable [Senger 1997]. It is said there that

> the measured data were the single most significant source of uncertainty in the entire validation process.

The second problem was to set up the parameters, exactly as they were set in Advisor. Taking all this into account, the difference between this simulation and the results from Advisor of 14% is considered acceptable, especially when considering that this simulation is intended for concept design. The big difference for the FUDS is due to the lack of models for the varying efficiency of the PMU, which becomes important in the FUDS. The figures are listed in **Tab. A.1**.

B. Parameter Evaluation Factor f

The effect of a parameter is visualised by seeing the effect of relative change. By this it is meant, if a variable is changed by a specific percentage, then what is the relative change on the predicted output variable.

First a datum point, x_d, is defined, which can be chosen such that the datum variable takes a reasonable value, reflecting what is currently used or achievable. After defining the datum point, which is used to compared to subsequent results, the factor f is defined as

$$f = \frac{r_O}{r_I} \tag{B.1}$$

where r_O is the relative change of the output and r_I is the relative change of the input. These ratios represent the relative change from the given datum point. Therefore

$$r_I = \frac{x_I}{x_{dI}} - 1 \quad \text{and} \quad r_O = \frac{x_O}{x_{dO}} - 1 \tag{B.2}$$

where r_I and r_O are the relative changes of the input and output respectively, x_I and x_O are the actual input value and output value respectively and x_{dI} and x_{dO} are the datum values of the input and output respectively, which is used to compare the other values. The values for f are interpreted as is shown in **Tab. B.1**.

Table B.1.: Interpretation of f

Value of f	**Interpretation**
$f = 0$	No dependency between r_I and r_O
$f > 0$	When r_I is increased/decresed then r_O increases/decreases
$f < 0$	When r_I is increased/decresed then r_O decreases/increases
$\|f\| \geq 0.5$	Strong relationship between r_I and r_O, if r_I is increased then r_O increases/decreases by at least half the increase of r_I
$\|f\| \geq 1.0$	Very strong relationship between r_I and r_O, if r_I is increased then r_O increases/decreases proportionally or more than the increase of r_I

C. Passive Energy Use of a Product due to its Mass

C.1. Inertia

Newton's law of motion states that the force F is the product of mass m and acceleration a, i.e.

$$F = m\,a = m\frac{dv}{dt} \tag{C.1}$$

integrating F with respect to distance, s, yields the work done W, i.e.

$$W = \int_{s_1}^{s_2} F\,ds = \int_{s_1}^{s_2} m\,\frac{dv}{dt}\,ds = \int_{v_1}^{v_2} mv\,dv = m\left[\frac{1}{2}v_2^2 - \frac{1}{2}v_1^2\right] \tag{C.2}$$

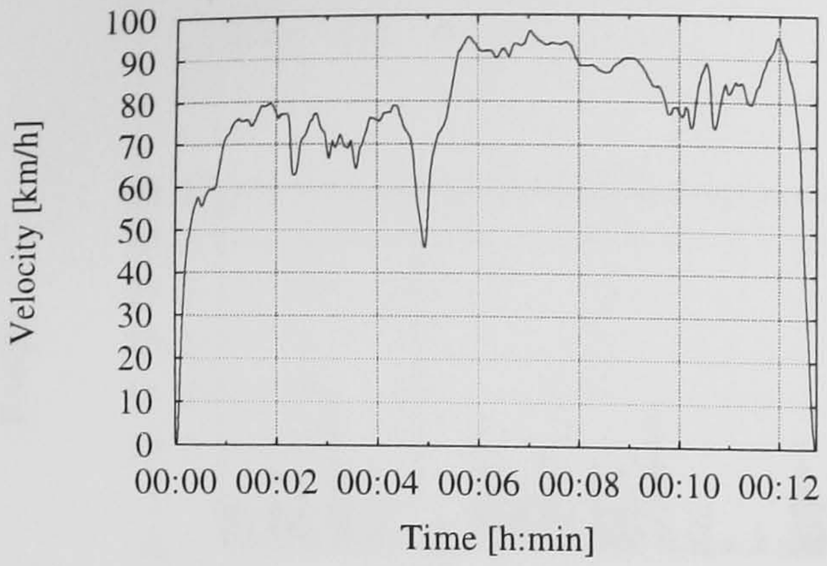
where v is the velocity. Therefore

$$W = \frac{1}{2}m\left[v_2^2 - v_1^2\right] = E_2 - E_1 \tag{C.3}$$

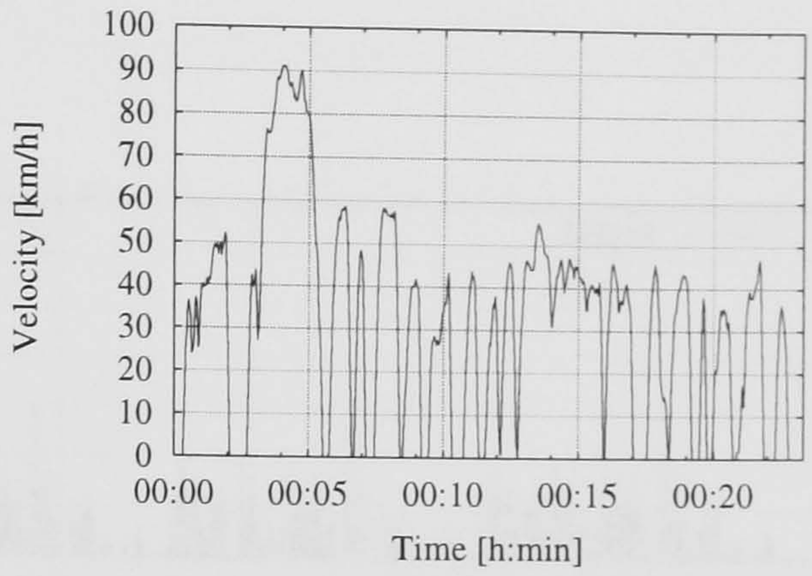
and it can therefore be seen that the work done is the difference between the kinetic energies E_2 and E_1. It can therefore be seen that when accelerating mass, energy is required to overcome the effects of inertia. The minimum energy that is required is the same as the difference between the kinetic energy at velocity v_2 and v_1.

Using an average drive cycle — such as the Federal Highway Driving Schedule (FHDS) (**Fig. C.1** a) and the Federal Urban Driving Schedule (FUDS) (**Fig. C.1** b) used in the USA, Canada and Australia — the differences in velocity can be used to determine the aforementioned minimum energy requirement.

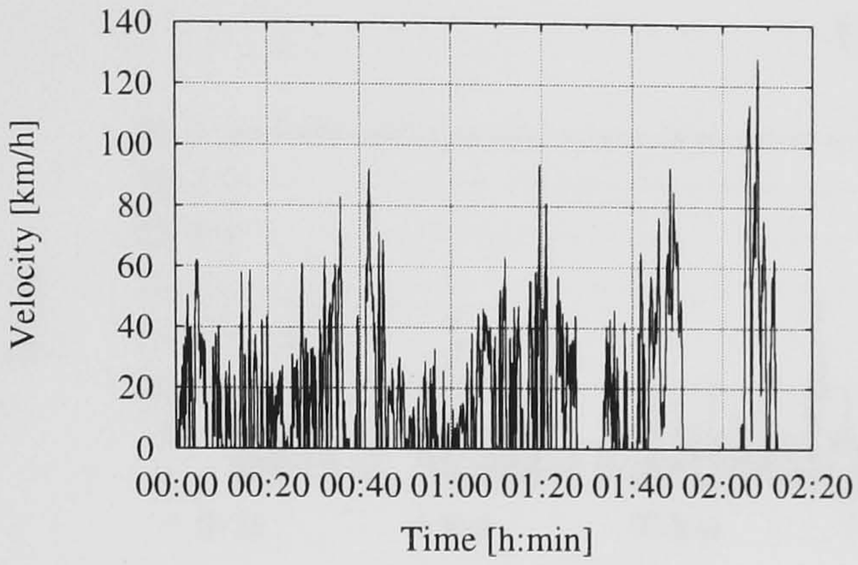
The average speed of the FHDS is 77.5 km/h and of the FUDS it is 31.6 km/h. The 'Athens' driving cycle is included to show how a possible 'worst case' driving schedule will increase the energy requirements due to heavy traffic leading to considerably more acceleration-deceleration cycles than the FUDS. This driving cycle may be more realistic for a metropolis rush hour (average speed 15.9 km/h). The Dutch bus driving cycle reflects the movement of a urban bus in a typical stop-and-go scenario. It's average speed is 21.0 km/h.



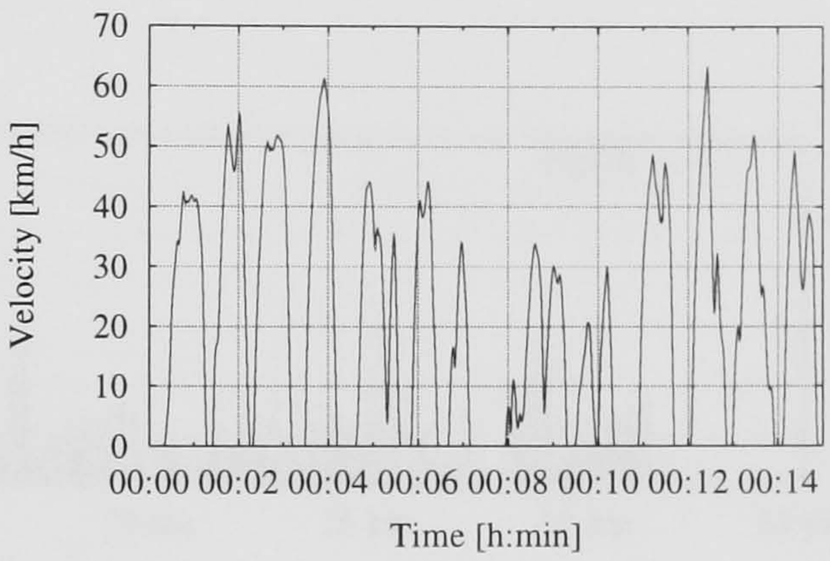
(a)



(b)



(c)



(d)

Figure C.1.: (a) FHDS, (b) FUDS (c) Athens and (d) Dutch bus drive cycles

Thus the total additional energy, E_a, due to the acceleration of the mass m over a drive cycle is the sum of W if $v_{t+1} > v_t$, i.e. acceleration.

$$E_a = \frac{1}{2} m \sum_t \left[v_{t+1}^2 - v_t^2 \right] \quad \text{for} \quad v_{t+1} > v_t \tag{C.4}$$

The fitted curves in **Fig. C.3** can be described by the following equations:

$$e_{acc(FHDS)} = 73 \frac{\text{J}}{\text{kg km}} \tag{C.5}$$

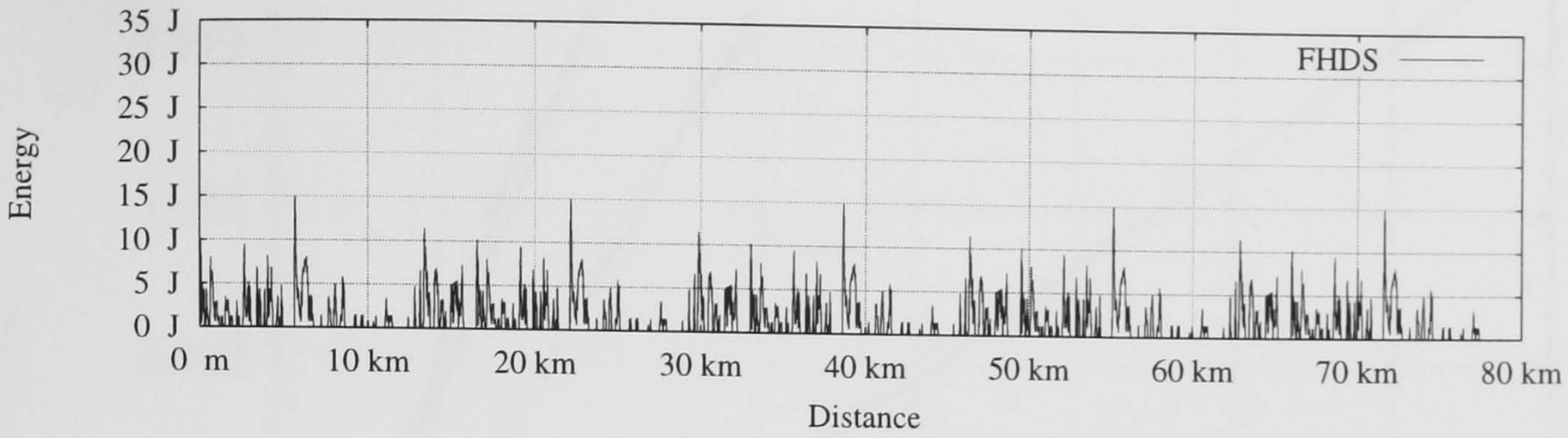
$$e_{acc(FUDS)} = 177 \frac{\text{J}}{\text{kg km}} \tag{C.6}$$

$$e_{acc(Athens)} = 290 \frac{\text{J}}{\text{kg km}} \tag{C.7}$$

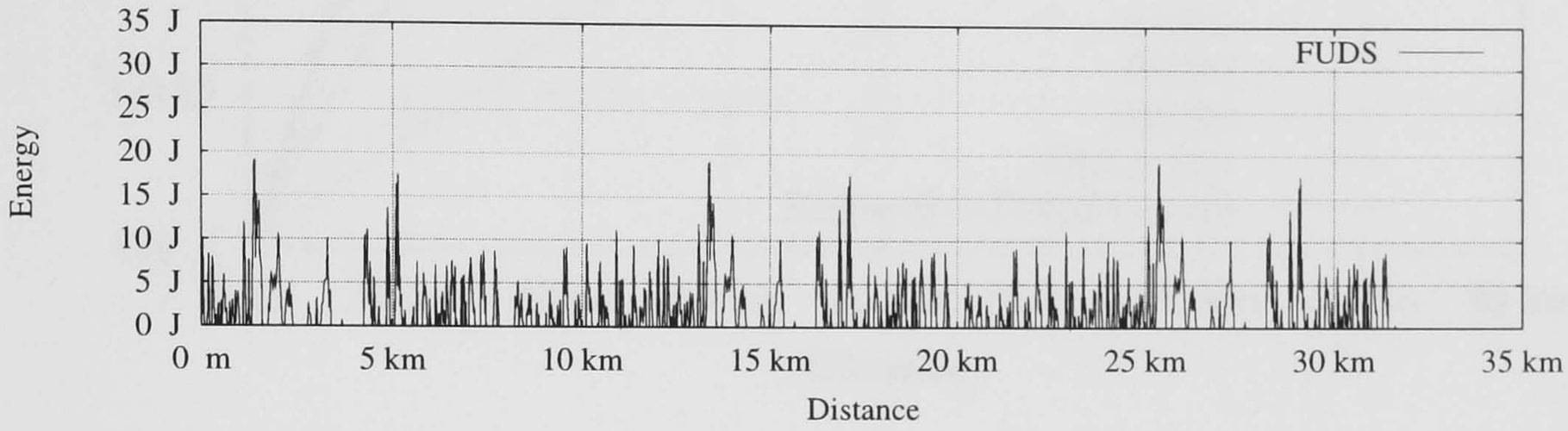
$$e_{acc(DutchBus)} = 263 \frac{\text{J}}{\text{kg km}} \tag{C.8}$$

According to USA regulations the FUDS and FHDS are used in a ratio of $55 : 45$ to determine the average fleet consumption of a manufacturer (Corporate Average Fuel Economy [CAFE]) which has to be below a certain value[1] [Beitz & Küttner 1990, p.

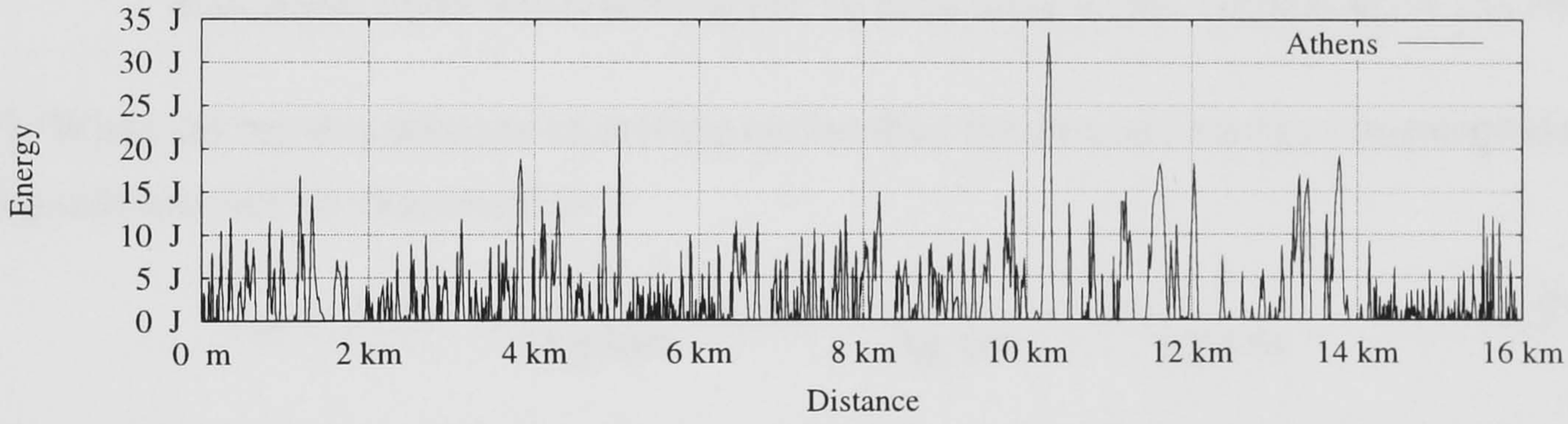
[1]The CAFE has to be below $8.55l/100km$ (above 27.5 mpg (here miles per US gallons)) (http://www.ita.doc.gov/industry/basic/cafe.html)



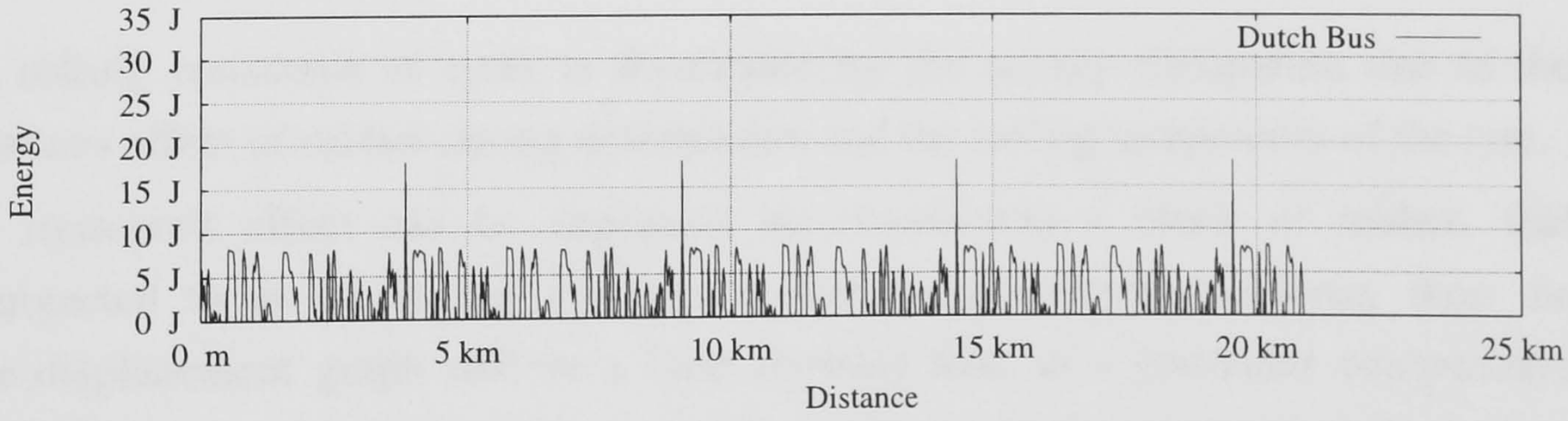
(a)



(b)



(c)



(d)

Figure C.2.: Instantaneous minimum energy requirement for the acceleration of 1 kg of additional mass when driving according the (a) FHDS, (b) FUDS, (c) Athens and (d) Dutch Bus drive cycles for 1h of driving

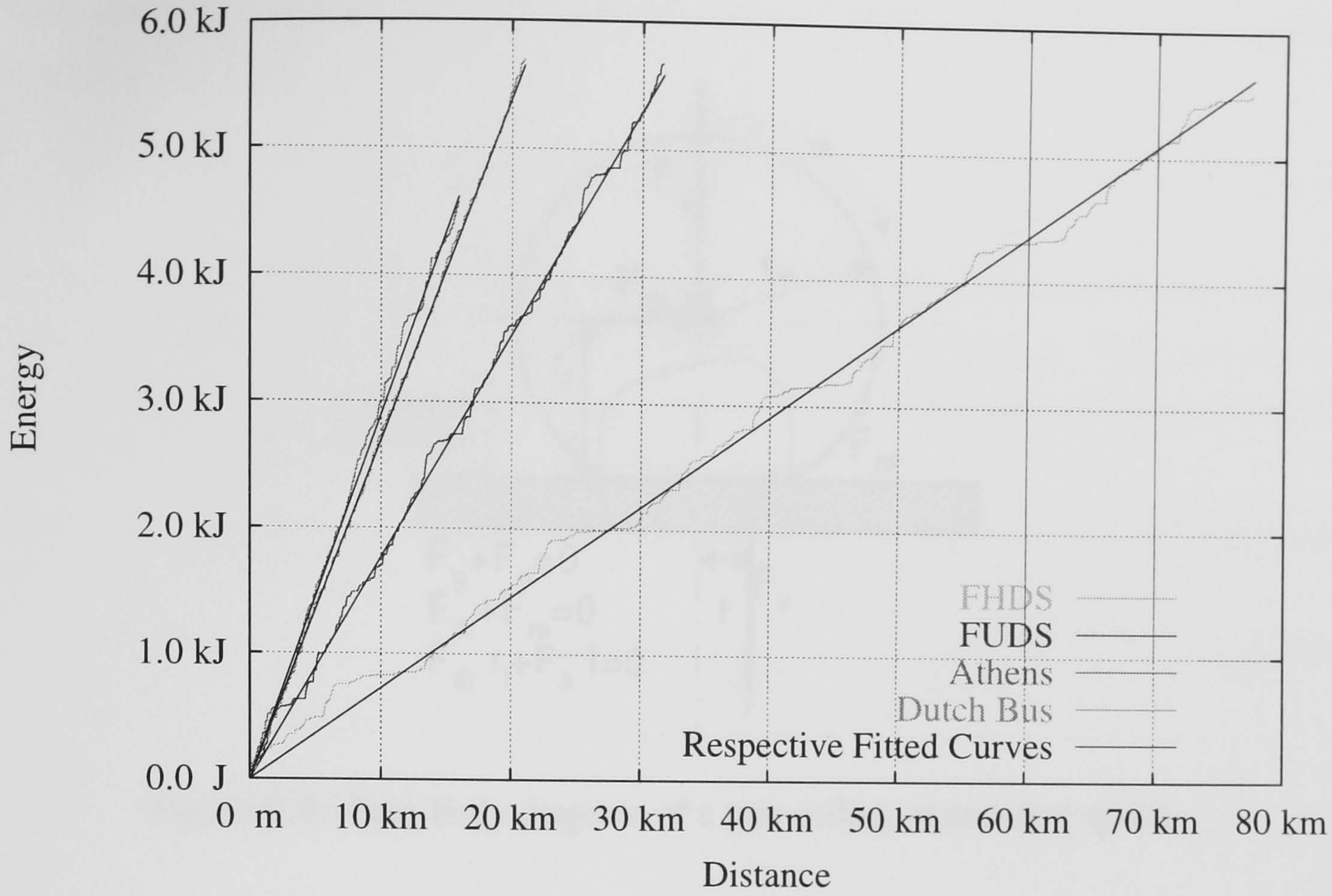


Figure C.3.: Cumulative minimum energy requirement for the acceleration of 1 kg of additional mass when driving for 1h according to the various drive cycles

Q35]. When taking this mixture of driving cycles then the average energy consumption per kg and km can be expressed as

$$e_{acc} = 0.55 \cdot 177 \frac{\text{J}}{\text{kg km}} + 0.45 \cdot 73 \frac{\text{J}}{\text{kg km}} = 130 \frac{\text{J}}{\text{kg km}} \tag{C.9}$$

C.2. Tyre Friction

The rolling resistance of tyres is dominated by the energy dissipation due to the hysteresis effect of rubber during deformation and the rolling momentum of the tyre.

The hysteresis effect can be explained by considering a block of rubber, that is subjected to an increasing and then a decreasing compressive force, then the force-displacement graph will be a loop showing that, at a particular compressive displacement, the force is greater when the rubber is being compressed than when it is being released from compression. Therefore the hysteresis in the tread rubber and the sidewalls of the tyre means that the elastic deformation requires a larger energy when being compressed, than it releases while being released from compression. The difference in energy is dissipated in the material and leads to an increase in temperature [French 1989].

The deformation of the tyre and the hysteresis in the tread rubber and the sidewalls of the tyre lead to the pressure distribution in the contact patch of a rolling tyre not being

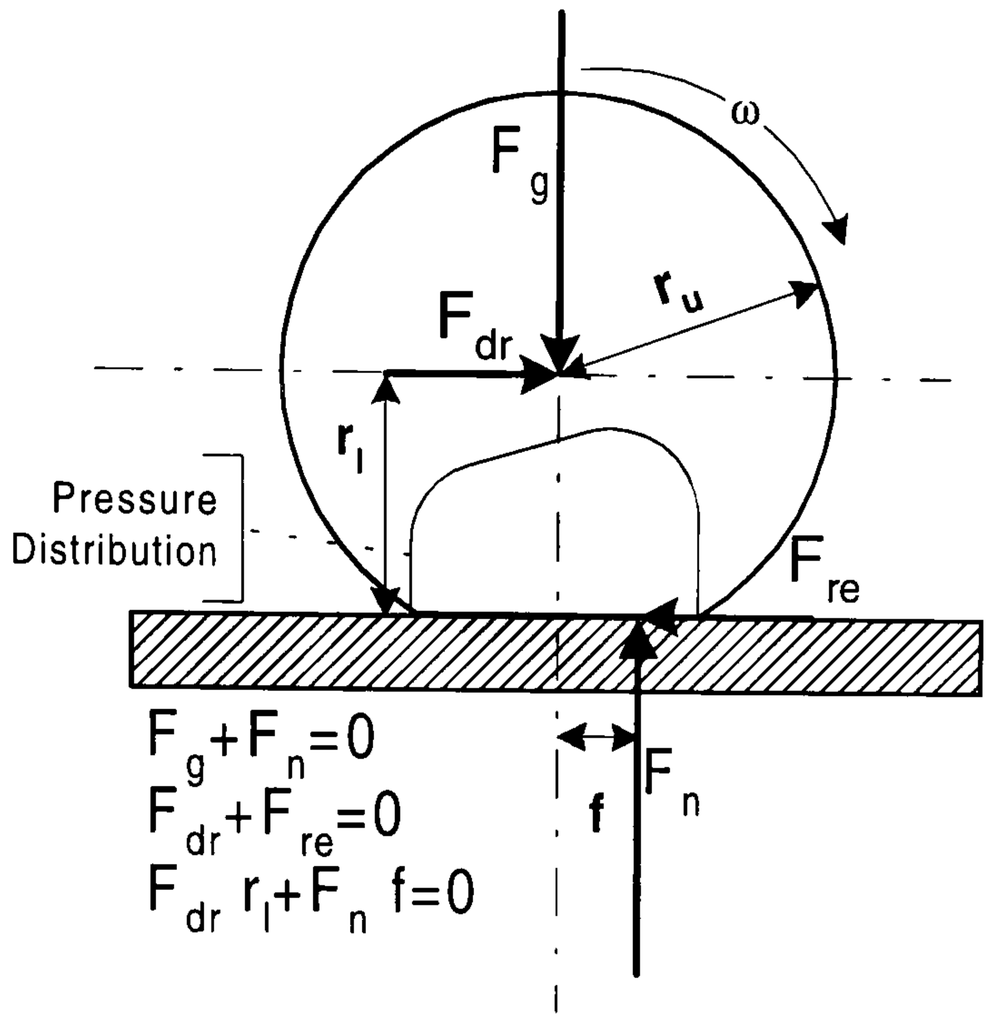


Figure C.4.: Free-body diagram of a tyre rolling at constant speed

symmetrical as is shown in **Fig. C.4**. There is a slight increase in pressure towards the front of the contact patch [French 1989, Segel 1975]. This requires a force, F_{dr}, to the hub so that the tyre-wheel system is in equilibrium. The existence of this small forward shift also means that there is a small shear force, F_{re}, acting at the tyre road interface in the opposite direction of F_{dr} so that it balances F_{dr}. From **Fig. C.4**, it can be seen that for equilibrium: $F_{dr} r_l = f\ F_n$. This is the rolling moment of a free rolling tyre. Here r_l is the loaded radius of the tyre. With $F_n = F_g$, the rolling resistance of the tyre is equal to the driving force, so that $F_{dr} = \frac{F_g\ f}{r_{loaded}}$. The rolling resistance coefficient due to the deformation, μ_r, is defined as the rolling resistance divided by the tyre load, i.e.

$$\mu_r = \frac{F_{dr}}{F_g} = \frac{f}{r_l} \tag{C.10}$$

It can be seen that the coefficient of rolling resistance increases the smaller the wheel radius and the greater the deformation.

The representation of the rolling resistance is simplified here and the actual coefficient of rolling resistance is determined experimentally. For pneumatic passenger car tyres on concrete asphalt the coefficient of rolling resistance, $\mu_r = 0.015$ [Adler 1987]. The coefficient of rolling resistance increases with

- increasing load
- decreasing tyre pressure
- increasing speed (relevant for speeds above 100 km/h [Adler 1987])

For overcoming the total rolling resistance over a distance, s, it is required to spend a minimum of energy E_{RR}

$$E_{RR} = F_{resist}\, s = m\, g\, \mu_r\, s \tag{C.11}$$

Therefore, if a product is carried by a vehicle then its mass will increase the overall mass and so E_{RR} will increase because of the increased tyre friction. This also shows that the energy spent due to the rolling resistance is not dependent on speed (below 100 km/h) but only depends on the total distance travelled.

This means that the added average energy, e_{RR}, due to carrying 1kg ($\mu_r = 0.015$) will be

$$e_{RR} = 147 \frac{\text{J}}{\text{kg km}} \tag{C.12}$$

C.3. Summary

Adding the *minimum energy requirement due to overcoming the inertia and tyre friction* then the total passive energy requirement per kg and km is

$$e_{pas} = e_{acc} + e_{RR} = 130 \frac{\text{J}}{\text{kg km}} + 147 \frac{\text{J}}{\text{kg km}} = 277 \frac{\text{J}}{\text{kg km}} \tag{C.13}$$

Assuming that the design life of a car is 200,000 km and the average conversion efficiency of the drive train is 30% then 1 kg of additional weight on the car will require an additional 4.3 kg of petrol[2] over its entire life only because it is moved.

Another simplified view is that when considering that a car weighs, say, 1200 kg then it will require a minimum of 3.6 l/100 km due to overcoming the effects of its mass[3,4].

[2]The specific heating value of Petrol is 42.7 MJ/kg [Adler 1987, p. 216]
[3]The density of petrol is taken as 730 kg/m^3
[4]Not considering the rotational inertia.