The Oil Point Method

A tool for indicative environmental evaluation in material and process selection

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Preface

This dissertation summarises the results of my work in the field of environmental evaluation in product development and Life Cycle Design, which I conducted at the Department of Manufacturing Engineering (IPT) of the Technical University of Denmark.

The project was funded as part of the research programme on Integrated Production Systems (IPS) under the Danish Technical Research Council (STVF).

I would like to thank my supervisors Dr. Torben Lenau, who initiated the project and who was a constant source of inspiration, as well as Dr. Michael Hauschild and Prof. Leo Alting for their support and many fruitful discussions throughout the project.

A special thanks goes to my colleagues from the PPS group Thomas Nissen, Michael H. Larsen, Gilad Langer, Christian Sørensen and Jakob Schnell.

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Abstract

The interest in sustainable patterns of production and consumption has been growing for over a decade, since the Brundtland Commission presented its report titled "Our Common Future" in 1987. The situation of the environment today - over six billion inhabitants on earth and a growing industrial activity world-wide -makes it increasingly evident that our current way of life is not sustainable.

A major contribution of society’s negative impact on the environment is related to industrial products and the processes during their life cycle, from raw materials extraction over manufacturing, transport, use to final disposal. Therefore, efforts focus on attempts to integrate environmental aspects into the whole process of product development and design. They often involve established tools and methods for environmental evaluation, such as formal Life Cycle Assessment (LCA). These tools and methods are, however, often relatively complicated and require more time, data and specific expertise in the field than designers usually possess. Furthermore, the detailed information required for an LCA are not available in the early stages of the product development process, where crucial decisions are made, such as the decision upon materials and manufacturing processes.

It is, therefore, a major challenge to develop tools and methods, which support the environmentally conscious selection of materials and processes while requiring only relatively little time and knowledge in the field of environmental evaluation and only approximate information about the product and its life cycle.

This dissertation addresses this challenge in presenting a method, which is tailored to these requirements of designers - the Oil Point Method (OPM). In providing environmental key information and confining itself to three essential assessment steps, the method enables rough environmental evaluations and supports in this way material- and process-related decision-making in the early stages of design.

In its overall structure, the Oil Point Method is related to Life Cycle Assessment - except for two main differences: the method considers exclusively primary energy relationships and it utilises material and process-specific indicators for the calculations.

The validation of the method is accomplished by means of five case studies, where results obtained with the OPM are compared to results obtained with two established methods for environmental evaluation: A formal LCA method and another indicator-based method.

A set of data for applying the method is presented including over 70 materials in pure or semi-finished form, over 20 manufacturing processes and some 20 other life cycle processes.

Other contributions of this research comprise an analysis of the current research in environmental evaluation and in environmental product development, a classification of tools and methods for environmental assessment in design and the identification of missing links between existing methods for environmental evaluation and their application in material and process selection in product development.

OliePointsMetoden

Et værktøj til indikativ miljøvurdering ved materiale- og procesvalg

Abstrakt (dansk)

Interessen for bæredygtig produktion og konsum er vokset konstant igennem mere end et årti, siden Brundtland-kommissionen forelagde rapporten ”Our Common Future” i 1987. Miljøsituationen i dag - med over seks milliarder mennesker på kloden og en globalt stigende industriel aktivitet - viser tydelig, at vores nuværende livsstil ikke er bæredygtig.

En stor andel af samfundets negative indflydelse på miljøet er relateret til industriprodukter og processerne i deres livscyklus, fra udvinding af råmaterialer over fremstilling, transport og brug til bortskaffelse. Der fokuseres derfor på at integrere miljøaspekter i hele processen af produktudvikling og design. Dette indebærer ofte anvendelsen af etablerede metoder og værktøjer til miljøvurdering, såsom formel livscyklusvurdering (Life Cycle Assessment, LCA). Men disse metoder og værktøjer er ofte relativ komplicerede og kræver mere tid, data og viden om miljøvurdering end designere som regel råder over. Derudover eksisterer den detaljerede information, som er nødvendig for en LCA endnu ikke i de tidlige faser i produktudviklingsprocessen, hvor afgørende beslutninger, såsom valget af materialer og fremstillingsprocesser, bliver truffet.

Det er derfor en stor udfordring at udvikle metoder og værktøjer som understøtter det miljøorienterede valg af materialer og processer, og som kun kræver begrænset tid og baggrundsviden om miljøvurdering samt kun overordnet informationer om produktet og dets livscyklus.

Denne afhandling griber denne udfordring an ved at præsentere en metode, der er tilpasset de krav som stilles af designere og produktudviklere - OliePointsMetoden (OPM). Ved at levere miljømæssige nøgleinformationer og indskrænke sig til tre essentielle vurderingstrin gør metoden grove miljøvurderinger muligt og understøtter dermed beslutninger omkring materialer og processer i de tidlige designfaser.

I sin overordnede struktur er OliePointsMetoden tæt relateret til Life Cycle Assessment - bortset fra to vigtige forskelle: metoden betragter udelukkende primærenergetiske sammenhænge, og der anvendes materiale- og processpecifikke indikatorer for beregningerne.

Metoden valideres ved fem case-eksempler, hvori resultaterne fra OliePointsMetoden sammenlignes med resultaterne fra to etablerede metoder til miljøvurdering: LCA-metoden UMIP og Eco-indicator 95, en anden indikator-metode.

Et datasæt, for anvendelsen af metoden er præsenteret, indeholdende mere end 70 materialer i ren form eller som halvfabrikat, mere end 20 fremstillingsprocesser og omtrent 20 yderligere livscyklusprocesser.

Arbejdet bidrager yderligere med en analyse af den nuværende forskning på områderne miljøvurdering og produktudvikling, en inddeling af metoder og værktøjer til miljøvurdering i design, samt identifikationen af manglede led mellem eksisterende metoder til miljøvurdering og deres anvendelse ved materiale- og procesvalg i produktudviklingen.

Die Oil Point-Methode

Ein Werkzeug zur indikativen Umweltbewertung bei Werkstoff- und Prozeßwahl

Abstrakt (deutsch)

Das Interesse an nachhaltigen Formen von Produktion und Konsum ist seit mehr als einem Jahrzehnt stetig gewachsen, seit die Brundtland-Kommission 1987 ihren Bericht mit dem Titel ”Our Common Future (Unsere gemeinsame Zukunft)” vorgelegt hat. Die heutige Umweltsituation – mit mehr als sechs Milliarden Menschen auf der Erde und einer weltweit wachsenden Industrietätigkeit – macht immer stärker deutlich, daß unser gegenwärtiger Lebensstil nicht nachhaltig ist.

Ein großer Anteil des menschenverursachten negativen Einflusses auf die Umwelt hängt mit Industrieprodukten und den Prozessen in ihrem Lebenszyklus zusammen, von der Rohstoffgewinnung über Fertigung, Transport, Nutzung bis hin zur Entsorgung. Deshalb werden Anstrengungen und Versuche unternommen, Umweltverträglichkeitsaspekte in den gesamten Prozeß von Produktentwicklung und -design zu integrieren. Diese Anstrengungen beinhalten oft die Anwendung etablierter Werkzeuge und Methoden der Umweltbewertung, wie z.B. formales Life Cycle Assessment (LCA). Diese Werkzeuge und Methoden sind jedoch häufig vergleichsweise kompliziert und erfordern mehr Zeitaufwand, Datenmaterial und spezifisches Fachwissen auf diesem Gebiet, als sie der durchschnittliche Designer und Konstrukteur besitzt. Darüber hinaus sind die für eine LCA benötigten detaillierten Informationen in den frühen Phasen der Produktentwicklung - in denen ausschlaggebende Entscheidungen wie jene über Werkstoffe und Fertigungsprozesse getroffen werden - nicht verfügbar.

Es ist daher eine große Herausforderung, Werkzeuge und Methoden zu entwickeln, die die umweltorientierte Auswahl von Materialien und Fertigungsprozessen unterstützen und dabei nur relativ wenig Zeitaufwand und Kenntnis auf dem Gebiet der Umweltbewertung sowie bloß ungefähre Informationen über das Produkt und dessen Lebenszyklus erfordern.

Diese Arbeit greift diese Herausforderung auf, indem sie eine Methode präsentiert, die auf die Erfordernisse von Designern und Konstrukteuren zugeschnitten ist – die ”Oil Point Method” (OPM). Indem sie umweltbezogene Schlüsselinformationen bereitstellt und sich auf drei wesentliche Bewertungsschritte beschränkt, ermöglicht die Methode grobe Umweltbewertungen und unterstützt auf diese Weise material- und prozeßbezogenes Entscheiden in den frühen Phasen von Design und Konstruktion.

In ihrer Gesamtstruktur ist die OPM mit Life Cycle Assessment verwandt – mit Ausnahme von zwei wichtigen Unterschieden: Die hier dargestellte Methode betrachtet ausschließlich Primärenergie-Beziehungen, und sie verwendet material- und prozeßspezifische Indikatoren für die Berechnungen.

Die Validierung der Methode erfolgt mit Hilfe von fünf Fallstudien, bei denen die mit der OPM erzielten Ergebnisse mit denjenigen zweier für die Umweltbewertung etablierter Methoden verglichen werden. Bei den Vergleichsverfahren handelt es sich um eine formale LCA-Methode und eine weitere indikatorbasierte Methode.

Zur Anwendung der Methode ist eine Datenbasis erarbeitet worden, die mehr als 70 Materialien in unverarbeiteter oder halbverarbeiteter Form, über 20 Verarbeitungsprozesse sowie ca. 20 andere Lebenszyklus-Prozesse umfaßt.

Weitere Beiträge dieser Arbeit bestehen in einer Analyse der aktuellen Forschung zu Umweltbewertungen und umweltbezogener Produktentwicklung, einer Klassifizierung der Werkzeuge und Methoden zur Umweltbewertung im Design sowie der Identifizierung von Lücken zwischen den bestehenden Methoden zur Umweltbewertung und ihrer Anwendung bei Werkstoff- und Prozeßwahl in der Produktentwicklung.

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1 Introduction

1.1 Background

Global concern

Just before the new Millennium had begun, the increasing population on Earth had exceeded the figure six billion [UNFPA 99]. The world-wide consumption of non-renewable materials and fossil fuels is increasing as well [WRI 99]. At the same time, scientists see a real risk that the global climate will change rapidly and dramatically over the coming decades [UNFCCC 92]. Such facts are the basis of an ever-growing global concern about long-term compatibility of human activity on Earth.

Focus on industrial products

Sustainable level

Industrial activity aiming at fulfilling customer needs by means of products is today recognised as a causal link between the facts mentioned above. Thus, environmental aspects of products are today in focus of efforts to minimise damage and to achieve a globally sustainable level.

Organisational and technical efforts

Current efforts to improve environmental behaviour of products cover processes at both the organisational and the technical level. Organisational efforts comprise the definition of dedicated legislative environmental requirements products have to fulfil (e.g. emission limits) and the implementation of environmental management systems (EMS) such as ISO 14001 and EMAS [ISO 14001, EMAS 93]. These efforts set a framework for legal issues and company-related organisational processes. Technical efforts focus on the optimisation of technical processes. In the beginning, this was done by means of end-of-pipe technology (e.g. filters). Today, focus is on process-integrated measures aiming at avoiding or minimising residues in the first place. Examples from this area of Cleaner Production are implementation of energy-saving technologies, closing of company-internal material loops, reuse of water and reduction or replacement of hazardous substances.

Efforts in product development

In strong relation to efforts on both the organisational and the technical level is product development, where products are defined. A generic obstacle for environmental efforts in product development is that the environmental aspects of the product have to be aligned with technical, economical, ergonomic and other aspects.

Another problem is that the future of a product after it has been sold cannot be foreseen precisely and that the performance of the product thus can only be estimated at the development stage.

Importance of materials in products

The environmental performance of a product is substantially influenced by the materials it is made of and by the processes, which take place in manufacture, transport, use and disposal. While processes happening after a product is sold - like transport, use and disposal - can only be influenced to a limited extent by a company, the preceding life cycle processes can be influenced relatively easy, as they are company-internal processes.

The decision upon the main materials of a product and related manufacturing processes happens company-internal and can, thus, be influenced completely. This makes the selection of engineering materials and manufacturing processes a crucial issue in industry when trying to develop environmentally improved products, see e.g. [Alting/Jørgensen 93, Alting 95].

Designers' influence

Designers play a central role in this context, as they actually make decisions upon which materials or processes to select. While investigating new solutions, they have to be aware of environmental consequences of the different options - ideally in quantitative terms. A couple of methods and tools have, thus, been developed to support designers and product developers in this environmentally focused selection process. Mirroring the complexity of the task, these methods differ in terms of level of detail and required environmental background knowledge.

Life cycle approach

There is, however, general consensus about the fact that such methods and tools have to be based on the life cycle approach. This means that the environmental behaviour has to be assessed over all stages of the product "life": from the extraction and processing of raw materials over manufacturing to transport, use and the final end of the product life. Such life cycle-based environmental assessment has been formalised and is generally referred to as 'Life Cycle Assessment' (LCA), see [ISO 14040, SETAC 93].

Life Cycle Assessment

1.2 Motivation and Goals of the Project

Need for innovative product and service concepts

When accepting the necessity to fulfil the needs of ever more people on the basis of a shrinking resource base and increasing pollution, new innovative concepts for products and services to fulfil those needs are a widely discussed option. One of the issues in question is, by which factor current industrial resource consumption should be reduced in order to reach a globally sustainable level (This "Factor discussion" is addressed in a section of Chapter 2). Here, designers – especially industrial designers - have a key role to play because their domain is to unfold creative and innovative potential.

Existing methods

Despite this circumstance, methods for environmental evaluation are often rather comprehensive and, therefore, less appropriate for designers. They often require co-operation with an environmental specialist. Such difficulties in application of comprehensive methods hinder their broad application, and they are unfortunately likely to be used to a much smaller extent in daily practice than desirable. Existing simplified methods, however, are either not full quantitative or expose difficulties in finding appropriate data.

Target group “designers”

The target group of the project comprises industrial designers, engineering designers and product developers in general. They all are referred to as “designers” in this thesis. The project, thus, focuses on individuals who are professionally involved in selection of materials and related manufacturing processes but who usually do not have specific experience in environmental evaluation.

The intention of this thesis is to introduce a quantitative method, which enables designers to perform rough environmental evaluations when they select materials and manufacturing processes in product development.

Aims

Overall aim with this Ph.D. project is to create a better understanding of the evaluation criteria important in materials and process selection. Focus is specifically on the environmental criteria of the selection.

Furthermore, the project aims at establishing and further developing methods, tools and data background, which enable industrial product developers to evaluate the environmental burdens related to alternative technological solutions in quantitative terms. As a constraint, these individuals are supposed to make such evaluations by themselves, i.e. without the help of specialists.

The result of the project shall make rough evaluations possible on the basis of limited prior knowledge about environmental evaluation methods and environmental data. Due to a number of associated simplifications, the outcome shall not be understood as a replacement but rather as a supplement to formal LCA methods.

1.3 Problem Statement and Hypotheses

The overall problem treated in this thesis is:

“How can environmental regard be integrated in decision-making of environmentally non-experienced designers when selecting materials and processes in early stages of product design and what are related methodological requirements and limitations?”

The two overall hypotheses are:

Hypothesis 1: "Environmental regard can be integrated in several ways but no existing method regards all crucial elements for making environmental evaluations in early design."

(This is argued in Chapters 4 and 5 with respect to guidelines, matrix-based and established indicator-based methods)

Hypothesis 2: "Although life cycle energy assessments are no valid metric to indicate *all* environmental implications they are valid as an indicator for *main* environmental implications during the product life cycle."

(Proof in Chapter 3 theoretically and in Chapter 7 via comparative cases)

1.4 Scope of the Project

The research field of environmentally conscious selection of materials and manufacturing processes (or just: Environmental M/P selection) is related to a number of other research fields, such as:

- Product development and design in general,
- Selection of materials and processes in specific
- Environmental science in general and
- Environmental assessment of products in specific

These partially overlapping fields are included in the scope of this project. 'Environmental management' and 'Eco labelling' are briefly addressed. This circumstance is outlined in **figure 1.2** in section 1.7.

1.5 Limitations

Indicative results

As for all simplified approaches in environmental assessment, the results of the envisaged evaluation method are intended to be of *indicative* character only. They shall give the right recommendations. This means that performing a full LCA would not lead to opposite decisions but maybe to more detailed ones.

Overall limitation can be seen in those of the related fields, e.g. uncertainties in the establishment of actual cause-effect chains (in environmental assessment) and the fluctuation of certain property values over time (in M/P selection).

1.6 Research Method and Working Techniques

Related to the Danish research programme on Integrated Production Systems (IPS) (under which this Ph.D. project was initiated), Jørgensen [92] proposed a two-stream model for research methods in applied science. This model, depicted in **figure 1.1**, recognises that research is either problem-based or theory-based.

In theory-based research, new scientific acknowledgement is reached by initially focusing on synthesis of models, which are then analysed with respect to e.g. usefulness in a given situation. Problem-based research, according to Jørgensen's model, starts off with an analysis of the problem in order to make a diagnosis. On the basis of this diagnosis, new solutions, e.g. in the form of methods, can then be synthesised. Scientific research results from either stream can, in a subsequent development activity, be adapted or implemented in order to lead to practical results.

The procedure followed in the present research project was clearly problem-based. Setting off with a problem description (given in section 1.3), existing approaches and methods were analysed resulting in a set of requirements upon a new, problem-adapted method. Such a method was then synthesised. Subsequently, this method was not implemented but rather verified by means of case studies, which were presented and discussed on seminars and conferences.

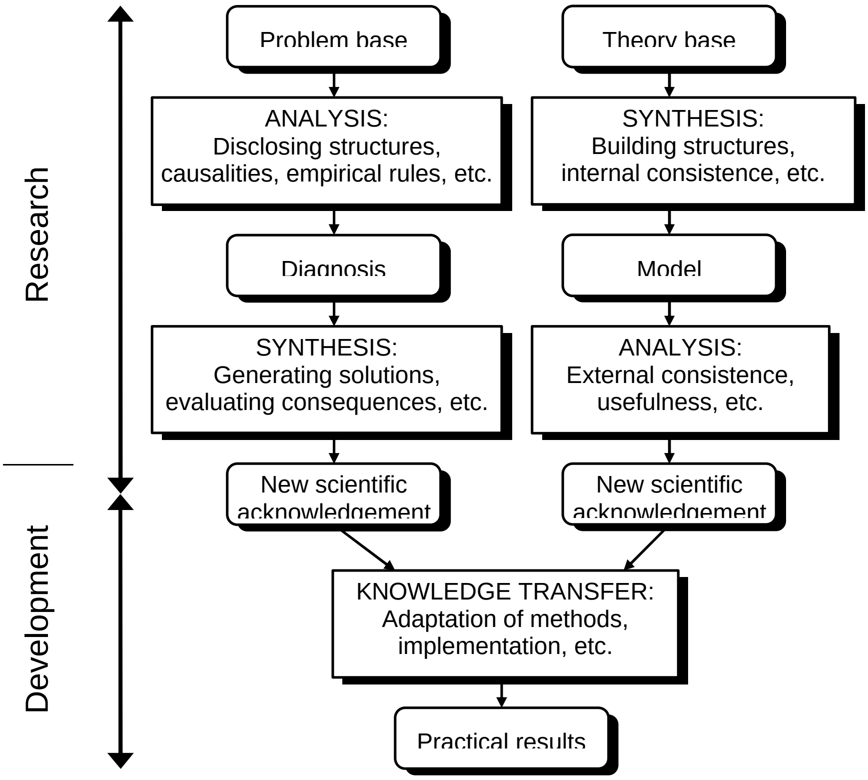


Figure 1.1 The two-stream model for research methods in applied science, adapted from [Jørgensen 92]

In the research process, scientific working techniques can be used in order to gain insight and to achieve results. These techniques can be of empirical or theoretical character. Empirical techniques are, for instance, questionnaires, interviews, workshops & seminars, case studies and literature studies. Theoretical techniques are e.g. modelling and theoretical reasoning, see e.g. [Schmidt/Carstensen 90].

The techniques used in this project include

- Literature studies,
- Theoretical reasoning,
- Case studies and
- Workshops & seminars.

The research process described above is mirrored in the structure of this thesis.

1.7 Structure of the Thesis

The structure of this thesis follows a general line of questions and problems related to the research topic. The chapters aim at providing answers and suggestions for solving these problems and questions.

After this introduction, the overall frame for the research work is outlined in Chapter 2. The following chapters then focus on remaining questions, which are given below

Chapter 2: “What is the problem with the Environment?” and
“Why worry about it?”

Chapter 3: “How can one ‘measure’ and quantify the extent of the problem?”

Chapter 4: “How is product design done?” and “What are the derived problems occurring when trying to design new products, specifically when trying to select materials and processes?”

Chapter 5: “Which approaches are suggested by others?” and
“What do they lack?”

Chapter 6: “Which solutions to these problems does the author see and suggest?”

Chapter 7: “How does the author prove that his suggestion works?”

Chapter 8: “Which solved and unsolved problems does the author see?”

Chapter 9: “What are the overall conclusions?” and ”What could further steps of research be?”

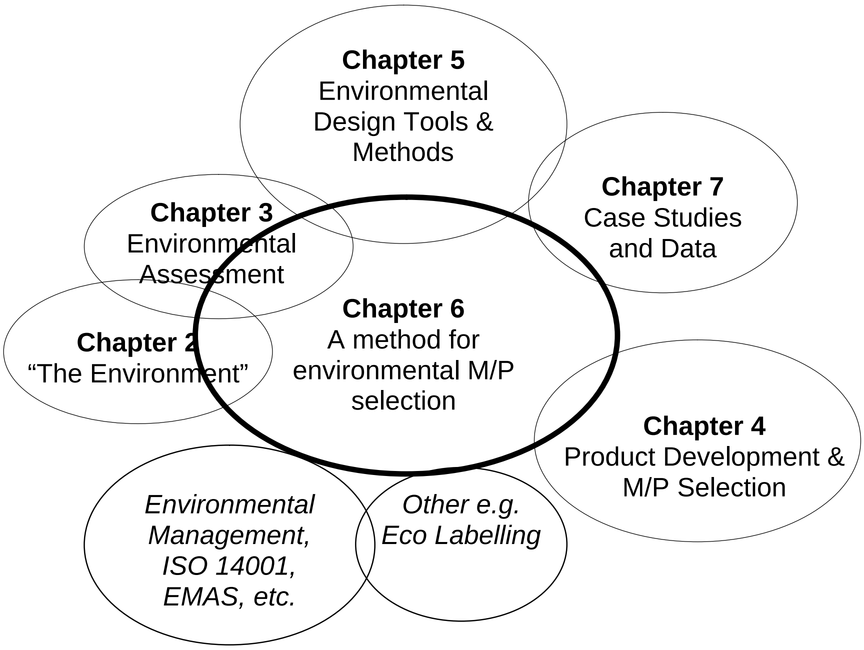


Figure 1.2 Fields related to environmental M/P-selection and respective chapters

Due to the overlapping character of the research fields, the separation of the contents of the chapters is not strict. Thus, some environmental design tools, dealt with in Chapter 5, are mentioned already in a section of Chapter 3 dealing with abridged environmental assessment approaches. Due to the same reason, environmental aspects are, for instance, also mentioned in Chapter 4, where it seemed appropriate to do so.

2 "The Environment", Environmental Concerns and the Concept of Sustainability

2.1 "The Environment" – What is that?

2.1.1 Terms

Before trying to improve the environmental situation it is useful to have an idea of what the object of improvement, namely "The Environment", is.

The Encyclopædia Britannica defines "Environment" as

> *"… the complex of physical, chemical, and biotic factors that act upon an organism or an ecological community and ultimately determine its form and survival"* [Britannica 00].

One can distinguish atmosphere (or: air environment), continental landforms and hydrosphere (or: water environment) as parts of the physical environment.

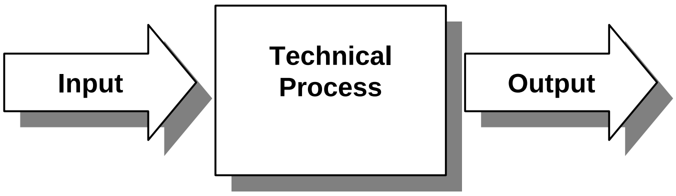
> This physical environment is the physical overall frame for ecosystems. An *ecosystem is the complex of living organisms, their physical environment and all their interrelationships in a particular unit of space* [Britannica 00]. (The Oxford English Reference Dictionary [Oxford 96] gives a similar definition where, however, "physical" environment is called "non-living" environment. It also states that "the relationships among species in an ecosystem are usually complex and finely balanced, and removal of any one species may be disastrous. The removal of a major predator, for example, can result in the destruction of the ecosystem through overgrazing by herbivores. Ecosystems can be identified at different scales: The global ecosystem, as an example for a large-scale ecosystem, consists of all the organisms living on Earth, the Earth itself (both land and sea), and the atmosphere above. A freshwater pond ecosystem, as an example for a small-scale ecosystem, consists of the plants and animals living in the pond, the pondwater and all the substances dissolved or suspended in that water, and the rocks, mud and decaying matter that make up the pond bottom".)

The principles underlying the study of ecosystems are based on the view that all the elements of a life-supporting environment of any size, whether natural or man-made, are parts of an integral network in which each element interacts directly or indirectly with all others and affects the function of the whole [Britannica 00].

An ecosystem can be categorised into its abiotic constituents, including minerals, climate, soil, water, sunlight, and all other non-living elements, and its biotic constituents, consisting of all its living members. The study of the relationships between living organisms and their environment is called *Ecology*. Linking abiotic and biotic constituents together are two major forces: the flow of energy through the ecosystem, and the cycling of nutrients within the ecosystem, compare [Britannica 00].

All *ecosystems* are contained within the largest of them, the ecosphere, which encompasses the entire physical Earth (geosphere) and all of its biological components (biosphere). Another part of the ecosphere is the technosphere. It comprises all things changed or produced by humans, compare e.g. [Schmidt-Bleek 98], p. 40.

Processes in the technosphere rely on input from ecosphere. More specific, technical processes require input in the form of materials and energy from ecosphere and produce desired effects, e.g. as products, and undesired effects, e.g. emissions to ecosphere.



Matter of concern is today, that inputs to and outputs from technosphere, i.e. from human activities, are about to exceed the capabilities of the (rest of the) ecosphere This refers specifically to the pull of resources and generation of emissions (see later section).

2.1.2 Environmental key dimensions

Taking the circumstances named above as a basis, one can describe the relation between technosphere and “The Environment” by using the following key dimensions:

- Resources, representing the input side
- Natural Environment, representing the output side and
- Population on Earth, determining the volume of input respectively output flows

Within each of the key dimensions *resources* and *natural environment* there are a number of categories to distinguish. Resources may be renewable or non-renewable, fuel-bearing or non-fuel-bearing, economically extractable or not, etc. Emissions to the natural environment can affect water, air and/or soil. All this can be contemplated on a local, regional or global scale.

It is important to be aware of the circumstance that, for a description of environmental relations, one can *choose* to make the description in one, two or all of the key dimensions and the related categories. A complete description of environmental relation, however, should include all dimension. Awareness of this circumstance is crucial to understand principles in environmental assessment. More about this in the next chapter.

2.1.3 Environmental mind-sets and scales

Is it "clear drinking water", "fresh air", "healthy trees"?

Environment is perceived individually. The single person might be concerned about local aspects, such as the condition of the trees in the forest nearby, the government of a country might focus on reducing the amount of waste produced by its society, while the multi-national company might see a problem in the depletion of copper resources. All bear an individual set of environmental focal areas in mind. This set of environmental focal areas may, thus, be called the "environmental mind-set" of that individual. Environmental mind-sets are the basis for setting environmental priorities. The definition of priorities is, therefore, also highly individual. In the examples above, the single person might want to improve nutrition conditions in the local forest, the government might promote recycling practices and the multi-national company might seek for substitute materials for copper in their products.

The environmental mind-set should be influenced by the scale of the environmental problem. Many large companies and governments, thus, set environmental priorities to problems of large scale, i.e. global problems.

To give examples, the environmental mind-set chosen in the EDIP method (see [Wenzel et al. 97]) are resources, natural environment, and working environment. The company Philips considers weight, hazardous substances, energy consumption, recycling/disposal, and packaging as being the most relevant parameters in relation to the Environment. (Mind-sets related to quality-aspects are discussed by Mørup [Mørup 93])

2.2 Environmental Concerns and their relation to products, materials and processes

2.2.1 Environmental concerns

Environmental issues have always accompanied human activities, especially those which were related to building and producing artefacts: e.g. constructing a shelter, finding or shaping simple tools, to name a few. Matter of concern in early ages, however, had been the influences of the environment on the artefact, i.e. the impacts that were likely to be imposed on the artefact by the environment.

Facing the problems of our present industrial production and consumption culture this view has broadened to include also the opposite, i.e. the impacts imposed on the environment *by* industrial products.

Environmental concerns, or environmental problems, exist in all key dimensions. Although their extent and seriousness may be discussed, just as the resulting measures to take, see [Lomborg 98], a number of concerns are generally accepted:

- Resources: Resources are finite and, in principle, precious (Resources are the totality of known or unknown existing matter of a material or substance. *Reserves* are that share of the resources, which is known and economically extractable.)

- Natural environment: Anthropogenic greenhouse effect, i.e. human-induced climate change (the "enhanced greenhouse effect"), Ozone depletion, Eutrophication of lakes, Deforestation and other phenomena

- Concerns related to population on Earth: The population on Earth has exceeded the six billion mark and is increasing [UNFPA 99]. The global standard of living - being proportional to energy and resource consumption - is rising.

2.2.2 Materials & The Environment

Materials influence the Environment throughout their whole life cycle: their extraction may be more or less impact-intensive, they may cause high or low impacts in manufacturing, use, transport and end-of-life.

Issues related to materials are:

- Energy content (primary or secondary material)
- Recycling (primary or secondary material, theoretically / practically possible recycling ratio)
- Density (weight in transport)
- Scarcity
- Renewable-or non-renewable (CO_2-neutral or not)

It shall be stressed here, that there is no such thing as an “environmentally friendly material”, when seeing environmental consequences in a product life cycle perspective, (compare e.g. [Ryding et al. 95], p. 157). A material can often be advantageous in one application or life cycle and disadvantageous in another. PVC, for instance, used in a product that is incinerated is not preferable.

The same material, however, used e.g. in a sandwich-layer in the floor panel of a train is preferable to most other materials due its low density and thus low weight in combination with good mechanical properties. As the environmental performance of a material always depends on the specific interactions during the life cycle of the product, generic statements about this performance are not possible.

The same is true for material classes. Natural materials, for instance, are often referred to as environmentally friendly and superior to e.g. fossil fuel-based materials, such as most polymers, because they are CO_2 neutral (i.e. they "release" only that amount of CO_2 at the end-of-life, which they have "absorbed" during their growth and do therefore not contribute to the Global Warming effect). However, if the application of natural materials, e.g. wood, requires a treatment with hazardous substances, e.g. for impregnation, their environmental performance in the product may well be worse than that of members from other materials classes.

2.2.3 Manufacturing processes & The Environment

Main impacts directly related to manufacturing processes result from:

- energy consumption (of the process equipment or machine tool),
- process waste (from work piece and tool wear) and
- hazardous substances directly or indirectly involved in the process.

Occupational health and the field of working environment are important aspects as well here, e.g. whether or not a process on average involves many accidents or produces toxic fumes etc.

Current tendencies in environmentally conscious manufacturing include e.g. [Melnyk/Smith 96, VDI wt 98, de Winter 98]:

- Near net-shape forming, reducing process waste and process energy
- dry machining, reducing the amount of hazardous coolants and lubricants involved
- precision casting, reducing the amount of process energy

It is important to notice that size and capacity of machine tools are typically overdimensioned, thus, seldom optimised for the process. Energy consumption (e.g. in the EDIP tool) expresses often not the actual process energy but the energy consumption of the machine tool including start-up and idle consumption [EDIP 98].

Overhead processes

A far more important aspect than these *direct* environmental impacts of the manufacturing processes themselves is, however, the impact created by the energy consumption of overhead processes accompanying the manufacturing activities.

In the company case studies conducted during the EDIP project (see [Wenzel et al. 97]), these *indirect* overhead processes, namely heating, lighting, air-conditioning etc. of the production site, turned out to cause between 50 and 75 % of the total impact of the whole manufacturing stage of electromechanical products. Although this share was determined for Northern European companies (where it is relatively cold and dark as compared to other regions), it can be assumed that overhead energy consumption also makes up a substantial share of the environmental impact of manufacturing activities in other regions. In warmer areas, increased air-conditioning would compensate for instance, less lighting and heating.

Marginal importance of manufacturing in product life cycle perspective

In a life cycle perspective, the manufacturing stage is very often of marginal importance compared to the stages materials production, use and end-of-life. The case studies described in chapter seven and general experience e.g. from LCA studies on electromechanical products (e.g. [Wenzel et al. 97]) indicate a share of manufacturing of usually less than 10 % of the overall life cycle environmental impact of electromechanical products.

2.2.4 Products & The Environment

Production volume and "rebound effect"

Products create environmental impact during their life cycle due to the processes they go through, see e.g. [Schott et al. 97]. Techniques and methods are discussed in this thesis and a new method is introduced. However, when talking about product-related environmental impact – especially in product design - one important parameter is often neglected: the production volume. If the single improved product does harm the environment less than its predecessor, the environment has not necessarily gained in the end. Because if there are more products sold than before (and this is, of course, usually intended by companies) then the overall impact on the environment may well become higher than with the old product. This is called the "Rebound effect", compare e.g. [Low/Williams 99].

Classic examples are environmentally improved (typically less fuel-consuming) passenger cars. Another one are mobile phones: in May 2000, about 375 million mobile phones were subscribed for on the global market. The forecast for end 2003 is almost 1.1 billion, [CSW 00]. It is obvious that environmental improvements have to take the dimension of production volume into account.

Structure

Concerning products, one can separate structure-related from the material-related impacts mentioned in section 2.2.2. The product structure, i.e. the arrangement and combination of its components, may hinder or ease activities in manufacturing (namely assembly), use (namely serviceability) and end-of-life (disassemblability and recycling of single materials). Design for Assembly, Modular design, Design for Dis-assembly and Design for Recycling are measures that may be taken to decrease structure-related impacts.

Critical stages

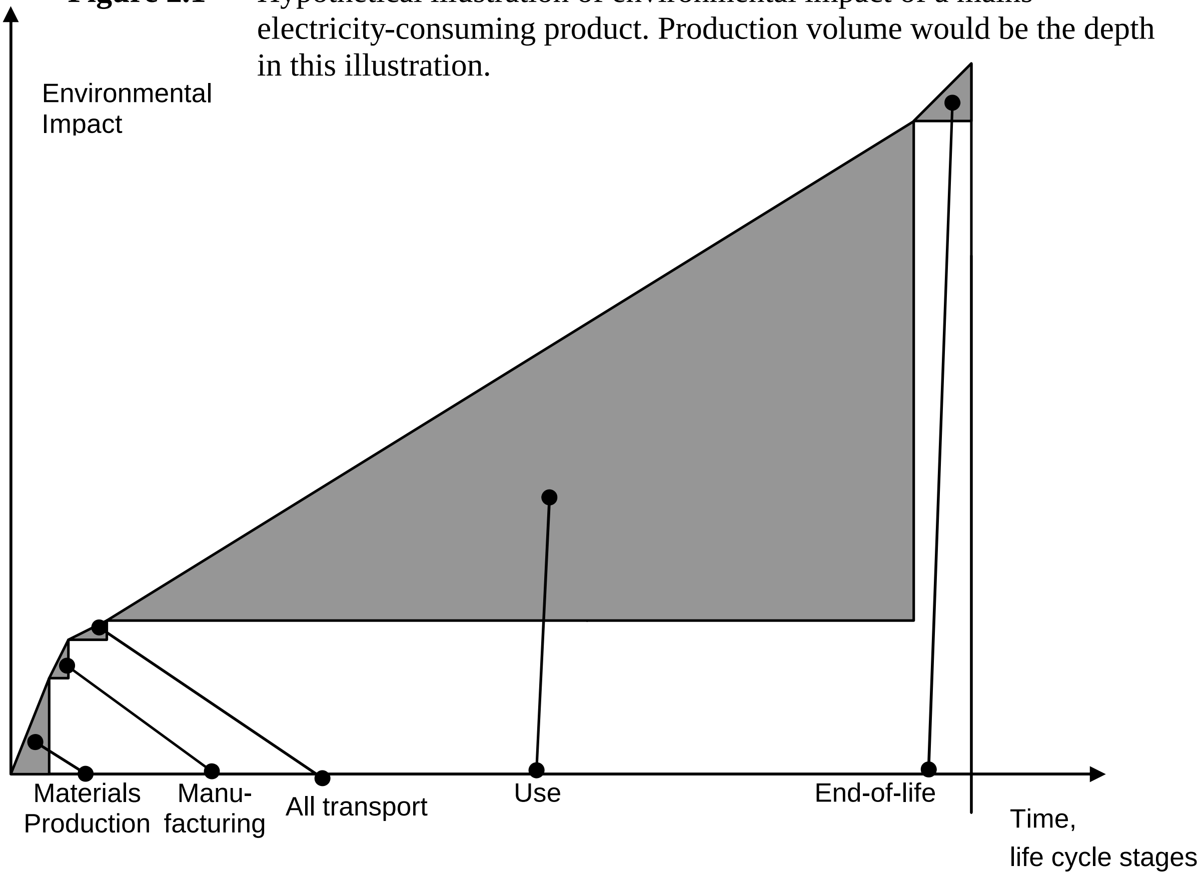
Typically environmentally critical stages in the life cycle of products are materials production, use and end-of-life. Manufacturing and transport often play a negligible role, especially for electro-mechanical products.

Product- and material-oriented efforts towards Re-use, Refurbishing, Recycling for application of same/comparable value, Recycling for application of lower value ("Downcycling") thus have primarily a positive influence in the resource dimension.

Again, the relations of the product and its users in these different life cycle stages are crucial for the environmental 'behaviour' or 'performance' of the product. Dannheim et al. [97] explain this for vacuum cleaners during use stage.

Lifetime of a product is another important factor. As will be explained in the next chapter, the environmental impact of a product is usually calculated for a period of service years. At the same time, environmental impact is, e.g. for energy-consuming products, cumulative over time. This is illustrated in **figure 2.1**, showing environmental impact over time for a hypothetical mains electricity-consuming product. The dominance of the use stage for this type of product is obvious. Production volume would be the depth in this graph.

Figure 2.1 Hypothetical illustration of environmental impact of a mains electricity-consuming product. Production volume would be the depth in this illustration.



2.3 The overall frame: Sustainable Development

A commonly accepted overall concept to solve environmental problems in all key dimensions is “Sustainability”. This term was coined by the World Commission on Environment and Development, usually referred to as the “Brundlandt commission” after its head, Gro Harlem Brundlandt. The Brundlandt report [Brundlandt 87] defines a Sustainable Development as a development that enables “current generations to fulfil their needs without compromising the ability of future generations to fulfil their needs”.

Sustainable development has not only environmental aspects but also economical, societal and ethical ones. Often, environmental aspects are in focus, however, when addressing Sustainability.

(One societal aspect of sustainability is surely, that “wealth” should be accessible to everyone. This includes, for instance, that newly developed products generally should be designed assuming that they are sold “all over” China or India. And: This shows that environmental implications may have to be balanced with societal ones.)

2.4 The concept of Industrial Ecology

The concept of industrial ecology was defined by Graedel and Allenby [Graedel/Allenby 95], p. 9:

> “Industrial Ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimise the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimised include resources, energy, and capital.”

Especially the integrative view on industrial systems as part of surrounding systems (e.g. ecosystems) and the environmental mind-set consisting of resources and energy are important elements here (compare section 1.1).

Graedel and Allenby see environmental impact as a result of three factors:

- population,
- Gross Domestic Product (GDP) per person (potentially corresponding with quality of life) and
- environmental impact per unit of per capita GDP (as the part influenced by technology)

In a so-called “master equation” they illustrate the relation of these major factors influencing environmental impact (**Eq. 1.1**).

$$Environmental\,impact = population \times \frac{GDP}{person} \times \frac{environmental\,impact}{unit\,of\;\; per\,capita\,GDP} \qquad (1.1)$$

While both population and GDP per person are expected to rise globally in the coming decades, the environmental impact per unit of capita GDP – being a technology-influenced term – offers the greatest hope for a transition to sustainable development, according to Graedel & Allenby. Modifying this term is the idea behind their concept of industrial ecology.

2.5 The "Factor discussion"

Regarding the aim of sustainability and overall *qualitative* equations like the one described above, it is undisputed that substantial reductions in environmental impact have to take place. The "Factor discussion" is the scientific and societal debate about the *quantitative* size of these necessary reductions.

Factor 4

Von Weizsäcker et al. [97] define a factor already in the title of their book "Factor Four: Doubling wealth - halving resource use". Their fundamental assertion is that resource productivity has to be quadrupled, in order to reach a necessary halving of resource consumption while allowing the standard of living to double, both to be reached by 2050. Concerning the standard of living they refer specifically to the global energy consumption, which is expected to double by 2050. At the same time, climate-harming emissions – resulting from combustion of fossil fuels - have to be halved by then. The environmental focus of the authors is on energy, resources and the transport sector, [Von Weizsäcker et al. 97], p. 20.

Factor 10

Schmidt-Bleek's scenario is more radical. He introduces the Factor 10 as a reduction target for the industrialised countries until 2025, see **fig. 2.2**. He also appreciates the necessity of halving emissions by halving (fossil fuel) resource consumptions in the coming decades (i.e. a Factor 2). However, he incorporates a right of the developing countries to rise their resource consumption above their present level in order to catch up with the western standard of living. First after a delay of about a decade the developing countries would then start their actual reductions. From this situation, he concludes that the industrialised countries have to reduce resource consumption to a tenth by 2025. In order to calculate impacts, Schmidt-Bleek et al. [98] suggest the purely mass-based MIPS method (Material Input per Service Unit). The more resource-efficient a process, product or service is, the lower the overall MIPS value.

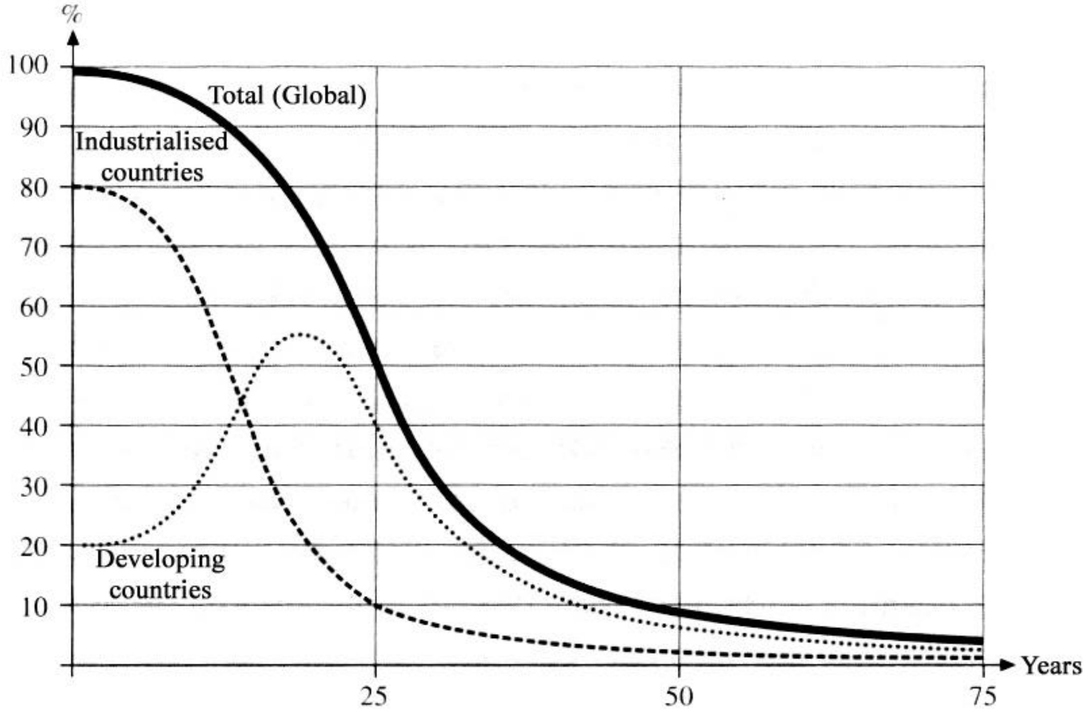


Figure 2.2 The graph explaining the Factor 10. If, in 25 years from today, the global resource consumption shall be reduced to 50% of today's level and if, at the same time developing countries shall initially be "allowed" to consume more resources than before in order to rise their standard of living, then the industrialised countries will have to reduce their resource consumption to about a tenth by 2025, [Schmidt-Bleek et al. 98]

All factor-related models assume that reduced input (in the form of resources) is directly proportional to reduced output (in the form of emissions). This, however, does not consider any intrinsic dangers incorporated in different substances and materials: Environmental impact related to (moving) one kilogram gravel is certainly not similar to that of one kilogram dioxin or radioactive material.

2.6 Summary

- The environment is an extremely complex system, which contains interacting ecosystems at different scales.

- The environmental performance of a material is always dependent on the specific life cycle of the product, which the material is used for.

- Environment is perceived individually (in a form that might be called "environmental mind-set"). Decisions concerning the environment, e.g. to improve certain aspects, are thus influenced by subjective factors.

- It is commonly accepted that regarding environmentally improved products, quantum leaps are required in order to reach a level of sustainable development (Factor discussion)

Trying to reduce the variety of understandings of "The Environment" to one common "environmental picture" with a number of parameters is difficult. Due to the fact, however, that broadly accepted targets have to be set in order to minimise environmental damage, the only pragmatic way is to find agreement upon the most dominant sources of concern. An example for this was the "Kyoto conference" in 1997, where over 100 countries agreed upon considerable reductions in emissions of CO_2 (carbon dioxide), methane, nitrous oxide and three other "greenhouse gases" in order to reduce Global Warming, compare [Kyoto 97, Kyoto 99].

A major contribution to the global CO_2 emission comes from electricity production, because it is to a large extent based on fossil fuels. As mentioned in a previous section, about 40 % of the CO_2 emissions of Denmark are based on electricity production - a fact that makes reduction of energy consumption a major environmental goal in this country.

Considering the situation today, where reduction of CO_2 emission is a globally accepted goal and where CO_2 emissions are to a great extent based on processes converting fossil energy into electricity or propulsion, it can be concluded that energy consumption can be seen as a common prioritised environmental factor.

The question whether something is environment friendly or not can not be answered objectively. For a general agreement, priorities have to be agreed upon. Due to today's situation, "consumption of fossil energy" can be considered as being an indicator for the priority "CO_2 emission".

There are four aspects of Sustainable Development: environmental, economical, societal and ethical ones. These have to be balanced.

One can distinguish three environmental key dimensions: resources, natural environment and the human dimension.

Concerning products, possible "rebound effects" have to be taken into account when making improvements on products because progresses regarding the single product, e.g. "10% less materials used", can be negatively overcompensated by producing a higher number of this product, e.g. twice as many. The three environmentally important dimensions concerning products are thus "time/lifetime", "environmental impact" and "production volume".

Sustainability is the overall goal. The best means we have today to "measure" sustainability is formal Life Cycle Assessment. This is described in the next Chapter.

3 Environmental Assessment

After having determined a need for action by exploring answers to questions such as “What is Environment?” and “Which environmental problems are we facing today?” in the previous chapter, other questions arise, for individuals as well as for designers, such as:

- “How can I measure ‘Environment’?”
- “How can I quantify the virtual ‘amount of Environment’ required or polluted by my product solution?” and
- “How can I compare alternative solutions with each other?”

The ambition to be able to answer such questions gave rise to the development of environmental assessment methods. Risk Assessments (RAs) and Environmental Impact Assessments (EIAs) allow answers to the above-mentioned questions related to chemical substances and industrial structures, see [Fava et al. 93, Consoli et al. 93]. Life Cycle Assessment (LCA) has been developed as an instrument for the environmental assessment of products, compare [Consoli et al. 93]. These product-related environmental life cycle assessments are in focus in this thesis, as materials and processes are selected with respect to producing products.

Today, a variety of LCA-based methods and tools exist; from full-scale formal Life Cycle Assessment to abridged methods and simple guidelines. They all try to give a sensible answer to one or several of the questions mentioned at the beginning of this section. However, they all have their advantages and disadvantages; their qualities, limitations and specific areas of application.

It is the goal of this chapter to give an overview over the field of environmental life cycle assessment as such and to make the reader acquainted with the main types of methods and tools existing to assess the environmental performance of a product, process or system. These methods are not necessarily developed for product development and design-related tasks. Product development-related methods are discussed in Chapter 5.

The chapter also treats data issues, and assessment metrics Furthermore, requirements to methods for environmental evaluation from the point of view of formal LCA are defined, and main environmental parameters for product evaluations are derived.

3.1 The term “Environmental Evaluation” in this thesis

“Assessment” and “evaluation”

Concerning methods, the term “environmental assessment” shall be understood as a synonym to “formal LCA of products” throughout this thesis, (despite the terminological discrepancy mentioned in the beginning of this chapter). Key word in the understanding is the term “assessment” as in LCA.

The term “environmental evaluation”, however, is more general and covers all kinds of methods including the more or less simplified methods. The method described in this thesis incorporates many aspects of formal LCA but has a crucial simplification in the input parameters considered (as it exclusively considers inputs of primary energy). It is, therefore, “only” referred to as environmental evaluation.

“Environmental Evaluation” in this thesis comprises the

- modelling of a product or product concept over the whole life cycle and the subsequent
- quantification of the relative environmental importance of the different stages including the determination of the environmentally most concerning stages.”

3.2 Fundamentals of Life Cycle Assessment (LCA)

3.2.1 Definition and structure

The general method developed to cope with the task of quantifying and in this way ‘measuring’ environmental damage related to products is “environmental Life Cycle Assessment”, LCA. LCA is sometimes read as “Life Cycle *Analysis*”. This, however, signals a too high degree of objectivity, as LCAs always involve subjective judgements, (see [Wenzel et al. 97], p. 27). Stressing the ‘life’-aspect, LCA is often referred to as ‘Cradle to grave’-Analysis. In German-speaking countries the terms “Ökobilanzierung” and “Umweltbilanzierung” are often used as synonym to LCA (even though the technique “Ökobilanzierung” originally only comprised plain input-output balances, i.e. only the Inventory part of LCA, see section 3.3.2). In French, the term is “ecobilan”.

In 1993 SETAC, the Society of Environmental Toxicology and Chemistry, defined LCA in the "Code of Practice" [Consoli et al. 93]:

> "Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements.

> The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance, recycling and final disposal."

A more recent definition of the International Organisation for Standardisation (ISO) reads [ISO 14040], (1997):

> "LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by
>
> - Compiling an inventory of relevant inputs and outputs of a product system;
> - Evaluation the potential environmental impacts associated with those inputs and outputs;
> - Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study
>
> (The term 'product' includes not only product systems but can also include service systems)
>
> The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences" [ISO 14040].

3.2.2 Applications of LCA

There are two principle applications for Life Cycle Assessments [Wenzel et al. 97, Curran 96]:

- Analysis, i.e. finding 'weak spots' in the life cycle of a certain product (and in this way determining focal areas for improvements) and
- Comparison, i.e. the comparison of two or more product solutions in order to determine the environmentally most favourable one.

For the results obtained from LCAs, there are various applications, for instance:

- Decision-making of governmental or non-governmental organisations
- company-internal information and decision-making,
- environmental labelling of product groups for consumer information (EU Flower, Nordic Svan, US Energy Star etc.)

In addition to these applications, TC 207, the Technical Committee 207 of ISO, which is in charge of developing LCA standardisation, mentions also that LCA can aid in the selection of relevant indicators of environmental performance [TC 207, 97].

A very positive "side effect" of performing an LCA is often that general information about the product's life cycle are generated for the fist time and that many relations and dependencies in the life cycle which had been unknown are revealed and documented.

LCAs are often retrospective. They mirror an environmental profile as it is ‘today’ or has been at an earlier point in time. It is, however, also possible to use an LCA of an existing product as a basis for making simulations. In simulations, parameters such as materials, use-pattern, lifetime, end-of-life processing etc. can be varied and respective scenarios can be compared. Such prospective LCAs provide answers to ‘what-if’ questions and are therefore very useful for environmental product development purposes to identify potential improvements.

3.2.3 The Life Cycle Concept

The idea of taking into account the whole life cycle of the product to be assessed is also referred to as ‘Life cycle thinking’ or the ‘Life cycle concept’, e.g. [Alting/Jørgensen 93]. It is today the generally accepted approach for making environmental evaluations.

There are differing descriptions of what a ‘Product Life Cycle’ comprises. In economical contexts, a product life cycle usually consists of the stages ‘Product definition’, ‘Product realisation’, ‘Introduction to market’, ‘Growth’, ‘Maturity’, ‘Saturation’ and ‘Decline’, see e.g. [Wiendahl 89], p. 54. In the field of environmental product development, a product life cycle may be outlined as the sequence of ‘Market need’, ‘Clarification of the task’, ‘Design’, ‘Manufacture’, ‘Operate’, ‘Recycle’ e.g. [Wallace 99]. These descriptions of product life cycles incorporate physical and organisational issues. In environmental assessment, however, the sole basis for the assessment is the *physical* life cycle, i.e. the sequence of stages, which the physical matter the product consists of, passes through. These life cycle stages are ‘extraction of raw materials’, ‘production/manufacturing’, ‘use’, and ‘disposal’ [ISO 14040]. ‘Transport/distribution’ may be allocated to the different stages but are usually specified as a separate fifth life cycle stage.

Throughout this thesis, the term ‘product life cycle’ covers *physical* processes in the five stages:

1. **‘Materials production’,**
   comprising all processes from ‘material in the ground’ to ‘pre-processed material at the factory gate’
2. **‘Manufacturing’,**
   comprising all processes taking place ‘inside the factory’
3. **‘Transport’,**
   being a compound stage of all transport processes between the different other stages
4. **‘Use’,**
   comprising all processes necessary to make the product function, e.g. electricity consumption, and to deliver this function in a certain quality, e.g. washing processes
5. **‘End-of-life’,**
   comprising all processes taking place after the product became

‘useless’ for its original user and is disposed of (i.e. re-use, disassembly, recycling, landfilling, etc.)

This description makes one circumstance very obvious: although it is the *product,* which is in focus in the assessment, it is in fact the *processes* within the life cycle stages, which are considered. This is so because it is not the product as such but rather the *life cycle processes* or *“unit processes”* that create *environmental exchanges.* These environmental exchanges, in turn, may represent or cause environmental problems.

3.2.4 Environmental Exchanges

Each process in the life cycle of a product has environmental exchanges. They are the process-related physical inputs from the environment and outputs to the environment. Inputs can, for instance, be materials or fuels. Outputs may be waste energy or residues of different kinds. The product itself is an output, too - usually the only wanted one (**fig. 3.1)**.

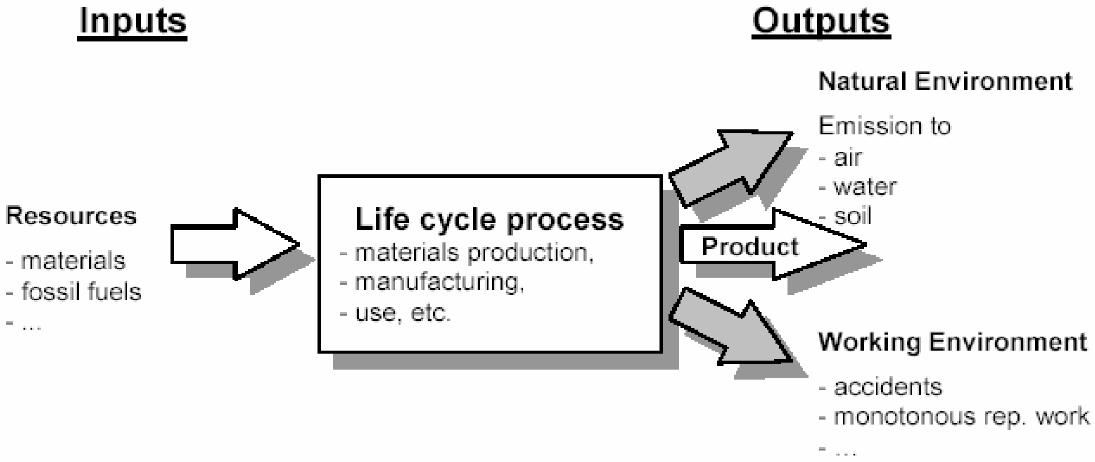


Figure 3.1 In- and outputs of a life cycle process

For Life Cycle Assessments, environmental exchanges are accounted for in their original or final form, respectively: Inputs are traced back to original extractions of resources from Earth (e.g. metals are traced back to extractions of metal ore, electricity is traced back to extractions of e.g. hard coal etc.) and outputs are sorted into final solid, liquid and gaseous fractions. Other outputs, e.g. surplus process heat, should also be accounted for.

Efficiency and yield factors

As regards inputs, actual quantities of extractions may be much higher than the amount needed: In order to obtain a couple of grams of gold, for instance, about a whole ton of ore has to be processed.

Another example is electricity production which, as a rough European average, is afflicted with an efficiency factor of 30 % . This means that about three times as much primary energy are required to produce a given amount of electricity. This is discussed in section 3.5. *Efficiency respectively yield factors* of transformation and processing of resources are, thus, crucial factors that have to be taken into account in an LCA in order to account for the full input side.

3.2.5 The ‘Functional Unit’

Focus in an environmental evaluation could be on various items: products (as it is today), production (as it used to be), societal activities (e.g. public and individual transport systems), activities of individuals (e.g. household activities) or the like.

An analysis of 22 activities in an average Danish four-person family, for instance, revealed that about a third of their resource consumptions and emissions are related to the preparation of meals. Another third results from car transport and room heating, the rest primarily from indoor free time activities (e.g. watching TV, listening to the radio) and activities related to clothing, hygiene, health and cleaning, [NCA 96a and NCA 96b].

As mentioned earlier, the focus of environmental evaluations in the context of this thesis is on products. In order to have a clear definition of the basis for the evaluation of the product and in order to facilitate comparisons of product alternatives a so-called ‘Functional Unit’ is defined. The Functional Unit describes the service the product delivers under

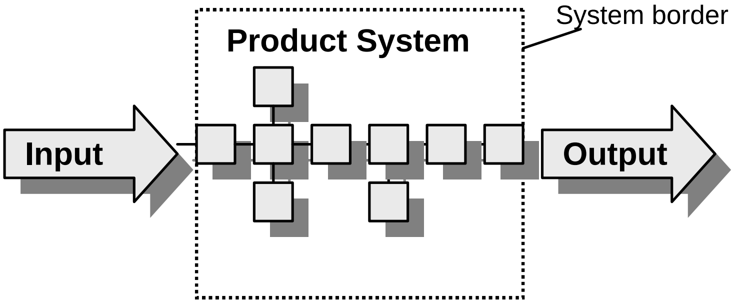
- Qualitative aspects, (e.g. “colour TV”)
- Quantitative aspects, (e.g. “20” screen, used for 5 hours per day”)
- Regional aspects (e.g. “in Denmark”) and
- Temporal aspects (e.g. “over 10 years” [i.e. the duration of the service within the expected lifetime of the product])

An example of a Functional Unit of a TV set could thus be *“Receiving and displaying PAL standard colour TV transmissions in Denmark on a 20” screen for 5 hours a day over a period of 10 years”*.

Especially the life time is of importance as environmental exchanges usually are expressed in units ‘per year’. In environmental comparisons of alternative product solutions, the duration of the service must be the same and the service must be experienced as comparable by the user with respect to all aspects, compare [Wenzel et al. 97], p. 44 f.

3.2.6 Product Systems

The totality of processes involved in a life cycle of a product is called ‘product system’. The product system is a model that comprises all processes involved in the life cycle of the product or service, the so-called ‘life cycle processes’, (compare sec. 3.2.4 Environmental Exchanges). The definition of the product system is a core element in environmental assessments.



All inputs and outputs (environmental exchanges), which cross the border of the product system are later accounted for (in the Inventory stage of an LCA, see section 3.3).

3.2.7 Inputs and outputs

In general, an LCA can consider environmental impacts on the input side of a product system and on the output side. On the input side, required resources (e.g. metals, fuels) and ancillary substances (e.g. chemicals, lubricants) are accounted. On the output side, emissions to air, water and soil are accounted. In the Danish EDIP method, also waste and impacts on the working environment are included.

Most LCA methods, irrespective of whether they are full or simplified approaches, focus on the output side, in particular on the emissions to air, water and soil. This has to be carefully observed when comparing results of different LCA methods (In the case studies in Chapter 7, this was done).

3.3 Formal Life Cycle Assessment

3.3.1 Major contributors

Formal LCA is the state-of-the-art instrument to make environmental assessments of products. Institutions having contributed in this field are:

- SETAC, the Society of Environmental Toxicology and Chemistry
  an independent non-profit organisation for environmental
  research and development, originated in the USA, there
  are a European and an Asian branch [SETAC 97]

- Research centres mainly in The Netherlands (CML) [CML 92], Sweden (IVL), Denmark (IPU) and Switzerland (ETH)

- The Swiss Federal Office of Environment, Forests and Landscape (BUWAL)

- National Environmental Protection Agencies, e.g. in Germany and USA.
- The International Organisation for Standardisation (ISO) in Switzerland and its national standards bodies

ISO co-ordinates the development of the 14000 series of standards, which are related to environmental management issues. ISO 14000 ff. relates to environmental management as such and environmental management systems (EMS), i.e. organisational aspects (This series is based on the British Standard BS 7750). In general, the 14000 series is comparable to the ISO 9000 series, which focus on “quality” and quality management systems (QMS).

In 1997, ISO released the first member of the 14040 series of standards for Life Cycle Assessment with “Principles and a framework for LCA” [ISO 14040]. This standard is based on SETAC work such as the “Guidelines for Life-Cycle Assessment: A ‘Code of Practice’” [Consoli et al. 93], which earlier on had become a de facto standard for LCAs.

3.3.2 ISO 14040

Basis for the following description is the ISO 14040 standard of 1997 [ISO 14040]. The standard defines a number of requirements on Life Cycle Assessments concerning:

- ‘key features’ of LCAs and ‘phases of LCAs’,
- the ‘methodological framework’ to be followed in the phases,
- ‘reporting’ issues and
- the ‘critical reviewing’ process.

Key features, for instance, are transparency of data and assumptions and description of data sources.

It is specifically stated, that there is *“no scientific basis for reducing LCA results to a single overall score, as this would hide existing trade-offs and complexities”*, [ISO 14040], p. 3. It is also stressed, that there is no single method for conducting LCA studies. Based on the ISO standard, organisations should have flexibility for user- and application-specific implementation of LCA.

According to ISO 14040, LCAs have to comprise four phases:

1. Goal & Scope Definition,
2. Inventory Analysis,
3. Impact Assessment and
4. Interpretation

Several direct applications of LCA are mentioned as well, such as product development or marketing. Phases and applications are given in **figure 3.2**.

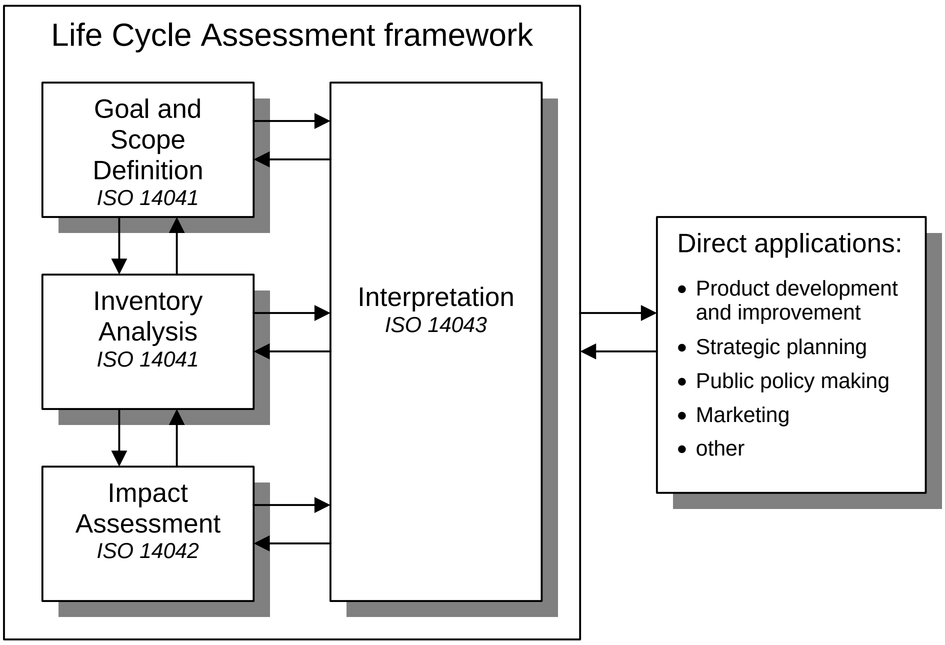


Figure 3.2 Phases of an LCA and direct applications, adapted from [ISO 14040], standards added

The recursive arrows in this figure indicate a crucial circumstance: Performing an LCA is an iterative process. The phases outlined below thus only indicate the overall sequence.

3.3.2.1 Goal & Scope Definition

In Goal and Scope Definition, the intended application, the reasons for carrying out the study and the intended audience are stated. In other words, in this phase answers to the questions “Why is the LCA carried out?” and “What shall the results be used for?” are determined. Both Goal as well as Scope Definition set the basic frame for the LCA and can, therefore, have considerable influence on the result of the study.

Fundamental aspects of the LCA to be stated in the Scope Definition comprise among others:

- the Functional Unit
- the product system and its boundaries
- allocation principles (e.g. the accounting of by-products)
- types of impacts to be considered
- major assumptions
- initial data quality requirements

Due to its complexity and importance for the other LCA phases, Goal & Scope Definition have been standardised in a separate standard, ISO 14041. Standards for the other phases are either already released or in the state of final draft, see [ISO 14042, ISO 14043].

3.3.2.2 *Inventory Analysis*

The Inventory Analysis (or just: Inventory) involves collection and calculation of data for the relevant inputs and outputs of the product system. The Inventory phase is usually the most time intensive period in an LCA study. Reasons are often lack of data or their poor quality. Additionally, iteration cycles may be necessary in this phase in order to determine, for which life cycle processes specific data are required.

The Inventory results in a long list of inputs of various kinds and outputs of different other kinds. Examples may be:

- On the input side: “50 kg wood” and “30 kg iron ore” etc. and
- On the output side: “3 kg CO_2”, “100 g SO_2”, “1 g radioactive waste” etc.

These figures are not directly comparable with each other and the question of “What is important, what not?” cannot be answered without deeper knowledge. For this reason, an Impact Assessment is performed.

3.3.2.3 *Impact Assessment*

The Impact Assessment phase aims at evaluating the significance of potential environmental impacts using the results of the Inventory Analysis. Steps included in Impact Assessment may be [ISO 14040], p.8:

- Classification; i.e. assigning the inventory data to impact categories
- (Normalisation i.e. the division of classified inventory data by a common denominator. Normalisation is not defined in ISO 14040, but mentioned as an optional step.)
- Characterisation; i.e. modelling the inventory data within impact categories
- Weighting; i.e. possibly aggregating the results in very specific cases, only when meaningful (Data prior to weighting should remain available in order to ensure transparency)

Classification

When inventory data are classified, they are assigned to different impact categories, such as Global warming, Ozone depletion, Photochemical ozone formation, Acidification etc. The number of impact categories considered can be chosen, when an LCA method is defined. Those impact categories chosen in the Danish EDIP method are given in **table 3.1**.

	Environment	**Resources**	**Working environment**
Global	Global warming Stratospheric ozone depletion	Fossil fuel, e.g. oil, coal, brown coal and natural gas	
		Metals, e.g. Fe, Al, Cu, Zn, Ni, Cr, Mn, Ag and Au	
		Other minerals, e.g. lime, phosphate and salt	
		Others	
Regional	Photochemical ozone formation		
	Acidification		
	Nutrient enrichment		
	Persistent toxicity - Human toxicity from the water compartment - Human toxicity from the soil compartment - Chronic ecotoxicity in the water compartment - Chronic ecotoxicity in the soil compartment		
Local	Ecotoxicity - Acute ecotoxicity in the water compartment	Biomass, e.g. wood, straw and grain	Cancer due to chemical substances
	Human toxicity - Human toxicity from the air compartment	Water, e.g. groundwater, surface water and water for hydro electric power	Damage to the reproductive system due to chemical substances
	Land filling - bulk waste (non-hazardous) - hazardous waste - slag and ashes - nuclear waste	Others	Allergy due to chemical substances
			Damage to the nervous system due to chemical substances
			Musculoskeletal injuries due to monotonous repetitive work
			Hearing impairments due to noise
			Grievous bodily harm due to accidents

Table 3.2 The EDIP method's assessment criteria, adapted from [Wenzel et al. 97], p. 51

Distance-to-target-principle

In practice, Weighting involves the definition of weighting factors. Those factors are used to multiply characterised inventory data in order to express the seriousness of the related potential effects. They are defined on e.g. international or national reduction targets (on political and/or scientific basis). The further away the current, say, emission of greenhouse gases is from the target, the higher the weighting factor and, thus, the more important the reduction of, in the example, greenhouse gases becomes. This commonly accepted weighting principle is called “distance-to-target-principle”.

Weighting factors, normalisation factors, choice of impact categories and the product modelling all introduce subjectivity into the LCA. Therefore, transparency is critical especially in Impact Assessment in order to ensure that assumptions and choices made are clearly described and, thus, traceable. (An exemplary calculation of Normalisation and Weighting on the basis of the EDIP LCA method is given in section 3.3.3)

Important comment

The Impact Assessment step is a controversial element of LCA as it involves value choices for instance in the selection of impact categories and characterisation models as well as in normalisation and weighting, compare [ISO 14042, Potting 00].

3.3.2.4 Interpretation

In the Interpretation phase of an LCA, findings from Inventory Analysis and Impact Assessment are combined in consistence with the defined Goal and Scope.

Interpretation includes:

- Identification of significant issues based on the previous phases of the LCA
- Evaluations considering completeness, sensitivity and consistency
- Conclusions, recommendations and reporting

3.3.3 EDIP and other formal LCA methods

ISO 14040 itself is no method for Life Cycle Assessment. It is rather a standardised framework for formal LCA methods, see **figure 3.3**.

Between 1990 and 1996, a comprehensive research project concerning environmental product development was carried out in Denmark under the title EDIP – Environmental Design of Industrial Products. The project was sponsored by the Danish Environmental Protection Agency and represented a collaboration between two departments at the Technical University of Denmark (Manufacturing Engineering and Control & Engineering Design), the Institute for Product Development, the Association of Danish Industry and five major Danish companies (Bang & Olufsen A/S, Danfoss A/S, Gram A/S, Grundfos A/S and KEWI Industries A/S).

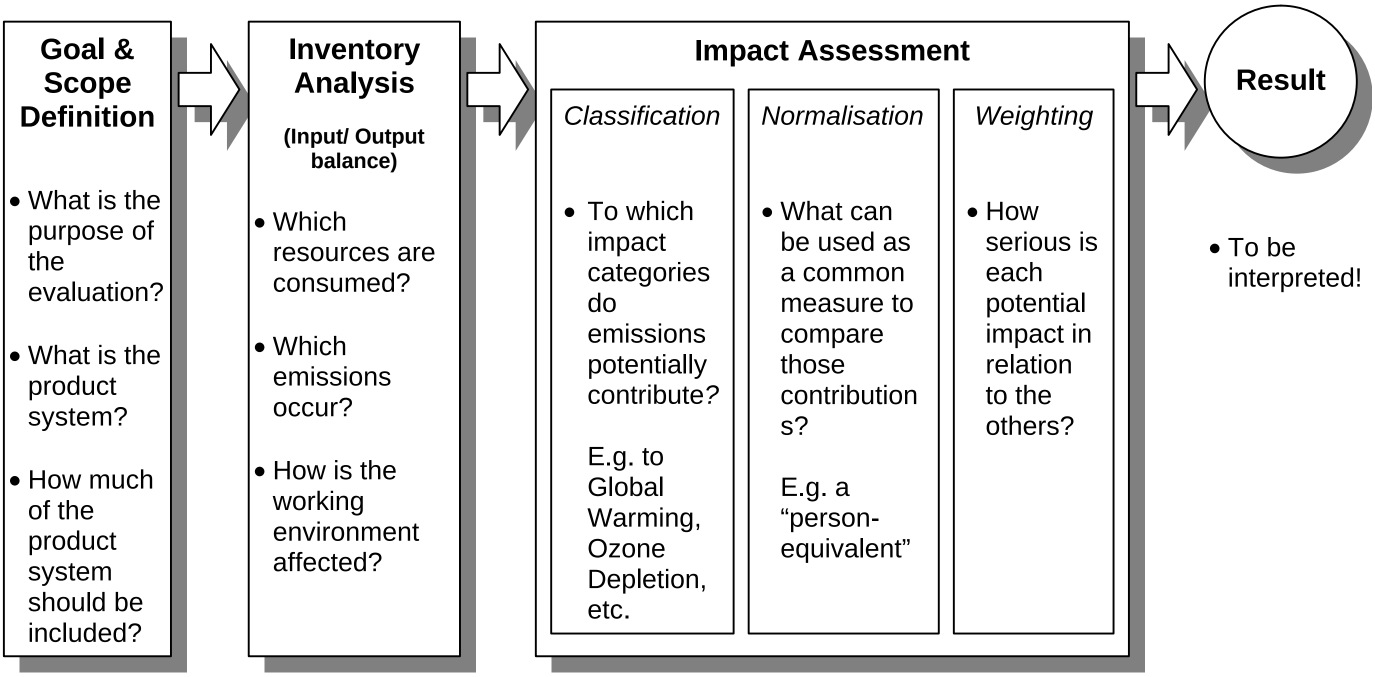


Figure 3.3 Framework for LCA methods and exemplary questions to be answered in the LCA stages

In the course of the EDIP project, a methodology for environmental assessment of products was developed concurrently with a set of tools, which were implemented in the product development procedures for a new generation of products of the participating companies. The project is described in detail in a series of books and a PC tool, e.g., [Hauschild/Wenzel 98, Wenzel et al. 97, Olesen et al. 96, EDIP 98].

Any product LCA involves the definition of the life cycle of the product in question. From all building blocks - or stages - in the life cycle, an input/output balance is made. While the inputs can be traced back to resource consumptions, the outputs can lead to impacts in the natural environment and in the working environment. Due to the fact, however, that the exact behaviour of the outputs in the environment is rarely known, the common expression used is *potential impacts* respectively *impact potentials*.

3.3.3.1 Key elements

The general classes of impacts considered in EDIP are:

- Resource consumption
- Impacts on the natural environment
- Impacts on the working environment

All three classes are fully described with normalisation respectively weighting factors. Most other methods only consider impacts on the natural environment. As normalisation basis, the average impact resulting from an average person is taken.

An example for the calculation of weighted data is given in subsequent section.

Another key element in the EDIP method is the definition of a reference product, e.g. the existing product which is to be environmentally improved. The reference product is assessed with a full formal LCA very similar to ISO 14040 (which was developed simultaneously with the EDIP project).

Improvement potentials are sought (in a phase comparable to ISO's Interpretation) and assessed as well by means of simulations. Most appropriate options can then be chosen.

3.3.3.2 *Calculation example for weighted data*

Comparison of 3 kg CO_2 with 1 g radioactive waste: The normalisation unit for "Global Warming" is "8,700 kg CO_2-equivalents per person and year". For "radioactive waste", the unit is "0.035 kg radioactive waste per person and year". The normalisation makes it possible to describe the 3 kg CO_2 output as 0.000,345 PE and the 1 g radioactive waste as 0.028,571 PE.

For most products, the values of person equivalents are smaller than 1, thus the typical unit utilised in LCA is milli-person equivalents, mPE. In the little example, the 3 kg of CO_2, being 0.345 mPE, are thus - at this stage of the assessment - quantitatively a by far less important contribution than the 1 g radioactive waste, which correspond to 28.571 mPE.

In a final *Weighting* step, the "relative seriousness" of the impact categories is mirrored. The mPEs are therefore multiplied by specific weighting factors. Those weighting factors, in turn, are - in the EDIP method - defined on the basis of, for example, emission reduction targets for the year 2000. The unit for weighted data is thus called "Target Person-Equivalents, PET", where T stands for "target" (PETs are also typically expressed as milli-PETs, mPET).

Those targets reflect environment-political reduction target values. The more serious an impact category is considered to be, the higher the reduction target value. The farther away from these reduction target values an impact category generally is, the higher the weighting factor. In the EDIP method, the weighting factors for CO_2 and radioactive waste are 1.3 and 1.1, respectively (Remark: For ozone depletion the EDIP-weighting factor is 23!). The weighted result of the 3 kg CO_2 is therefore 0.449 mPET, while the 1 g radioactive waste equals 31.428 mPET, which is extremely higher. The described procedure of transforming Inventory Data to Weighted Data is shown in **figure 3.4**.

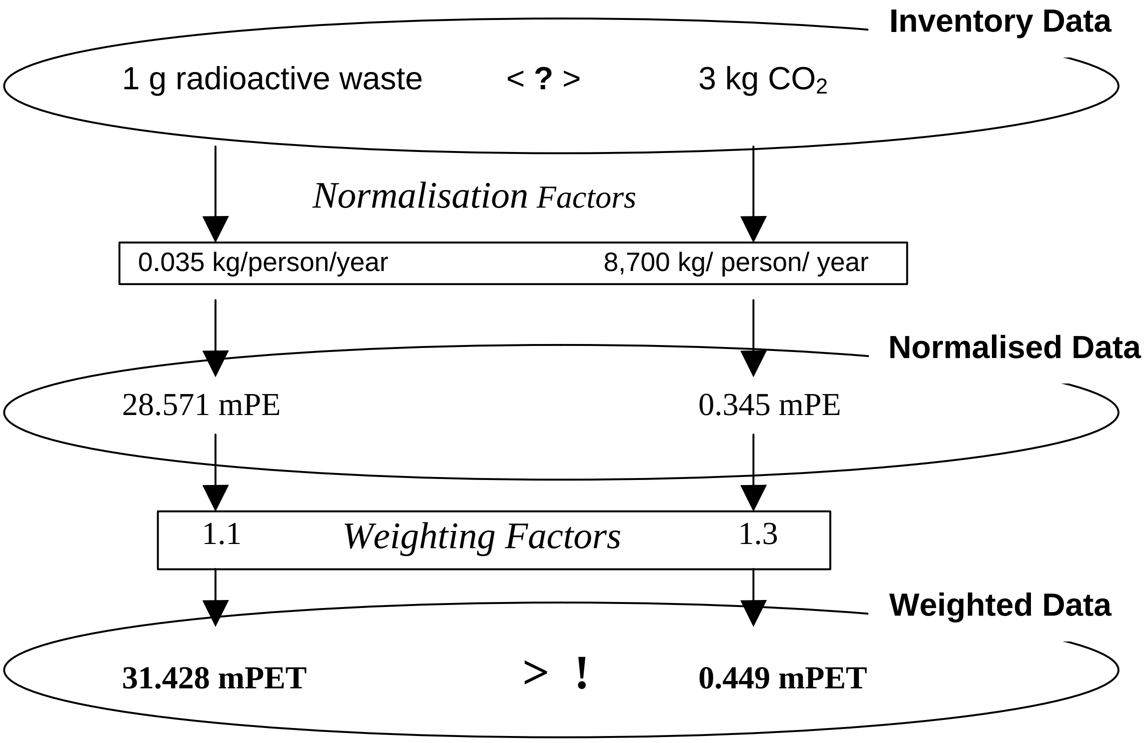


Figure 3.4 Transformation of non-comparable Inventory Data to comparable Weighted Data

The EDIP method comprises two approaches and procedures: A more qualitative one for the product developer, which is mainly based on guidelines, and a comprehensive, quantitative one for the environmental specialist within a product development team, which represents a computer supported formal LCA method.

3.3.4 Differences of formal LCA methods

Due to, for instance, the differences in products but also in the aim of an LCA, there are today several life cycle based assessment methodologies considering different classes of impacts, different normalisation units and/or different weighting principles and weighting factors. Other main approaches were developed by CML (Leiden, The Netherlands) and BUWAL (Bern, Switzerland)

Formal LCA methods can differ in following aspects:

- Overall impact classes taken into account (Resources, Natural environment, Working environment)
- Impact categories taken into account (Global warming, ozone depletion, acidification, etc.)
- Normalisation references (average European values, average global values)
- Weighting factors (depend e.g. on national reduction targets)

3.4 Abridging and simplifying Life Cycle Assessment work

Full formal Life Cycle Assessments require a high effort in time (e.g. for inventory data collection) and expert knowledge. LCAs are, however, always performed in order to support a specific decision (that has to be defined during Goal & Scope Definition) and depending on this decision, abridgements may be made. General decisions, for instance, may well be made on the basis of average data, thus avoiding a dedicated data collection, compare [Christiansen 97, Graedel et al. 95a, SETAC 99].

3.4.1 Full, Screening and Matrix LCAs

Wenzel suggests a categorisation of LCA work into three basic levels [Wenzel 98]:

1. Full LCA
2. Screening LCA
3. Matrix LCA

In this categorisation, full LCAs give *quantitative results* and require *new data* collection. Calculations are typically made on a PC-tool.

Screening LCAs are appropriate when *quantitative results* are needed, and *readily available data*, e.g. from databases are sufficient. Calculations are typically done by means of a PC-tool.

Matrix LCAs can be used when *qualitative or semi-quantitative results* are sufficient. They typically involve calculations by hand or pocket calculator.

Wenzel illustrates related time-requirements in the way shown in **figure 3.5.**

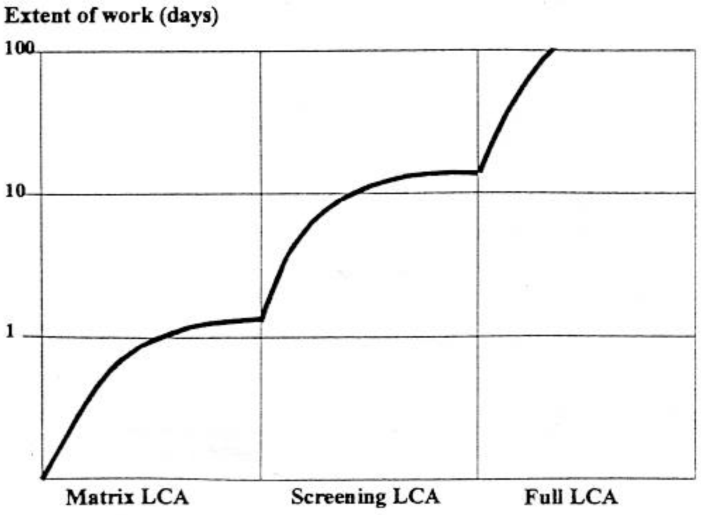


Figure 3.5 Extent of work required at different LCA levels. Rough average time estimates [Wenzel 98]

Roughly speaking, a Matrix LCA will take not more than a few days, a Screening LCA a few weeks and a full LCA everything above that.

The structure of a Screening LCA is obvious; it is similar to a full LCA but relies on readily available data, which results in a substantial reduction in time.

Matrix LCAs base on the very important fact that underlying *causes* of environmental impacts can be tracked down to either of four sources:

- **M**aterials (Resources),
- **E**nergy
- **C**hemicals and
- **O**ther sources (e.g. monotonous work)

Table 3.2 provides an overview over impact categories related to M, E, C and O

	Environmental impacts	Resource consumption	Impacts on the working environment
Materials	Bulk waste	Resources used in	
	Slag and ashes	materials	
		Mainly reversible	
		consumption	
Energy	Global warming	Energy carriers, especially	
	Photochemical ozone formation	fossil resources and wood	
	Acidification	Mainly irreversible	
	Nutrient enrichment	consumption	
	Bulk waste		
	Slag and ashes		
	Nuclear waste 1)		
Chemicals	Ozone depletion	Resources used in the	Impacts related to chemical
	Photochemical ozone formation	production of	exposure: cancer, damage to
	Persistent toxicity	chemicals	the reproductive system, allergy
	Ecotoxicity		and damage to the nervous
	Human toxicity		system
Others			Monotonous repetitive work,
			noise, work accidents

Table 3.2 Assessment parameters in the LCA method covered by M, E, C, and O, adapted from [Wenzel et al. 97], p. 136, 1) *Nuclear waste added by the author*

A Matrix LCA developed by Wenzel et al. [97] is called MECO matrix, as an acronym for the four types of causes.

In a Matrix LCA, these sources are listed against the life cycle stages of the product and *expected* impacts are filled in as matrix elements, see **table 3.3**.

	Life cycle stage				
Causes of environmental impact	Material Production	Manufac-turing	Trans-port	Use	Disposal
Material	Cu, Zn				Cu + Zn loss, Cu in steel
Energy [MJ]	35	18	2	Friction: 65 Heatloss: 800	Steel contamination: 950
Chemicals		Greasing and de-greasing agents			
Others					

Table 3.3 Matrix LCA of a mechanical valve for a central heating plant, Material: Brass, Weight: ca. 500 g, Life time: ca. 40 years, adapted from [Wenzel 98]

Other Matrix LCA approaches include (see section 5.3 in Chapter 5):

- Materials, Energy and Toxic substances (MET, Brezet/van Hemel 97, Kalisvaart/Remmerswaal 94] or

- Materials, Energy and outputs in the form of Solid, Liquid and Gaseous residues [Graedel/Allenby 96, Graedel et al. 95a] (This is a different approach than the other two as it includes outputs but no chemicals as input)

3.4.2 Indicator-based LCAs

Another approach to simplify LCA work is done in indicator-based methods. The aggregation principle for a commonly used indicator-based method, the Eco-indicator 95 [Goedkoop 95 a, b] is shown in **figure 3.6**. Here, normalised and weighted data are aggregated to a single indicator value (e.g. 5 millipoints per kg material) as shown in the right end of figure 3.4. The “Effect” column in this figure, refers to the impact categories considered in Eco-indicator 95. These cover only impacts on the natural environment. Working environment is not considered and resource consumption, e.g. metals, only indirectly by means of the emissions from related energy consumption. When, for instance, a ton iron ore is extracted, this requires energy. If this energy was produced by means of burning of fossil fuels, the related emissions are accounted in the Eco-indicator 95.

The Eco-indicator 95 method has been revised in 1998 and 1999 [Goedkoop et al. 98, Goedkoop/Spriemsma 99]. It now includes a more differentiated weighting step, among other things. Basis for the comments and calculations in this thesis is, however, the ’95 edition as this was fully described at the time, when the case studies in Chapter 7 were calculated.

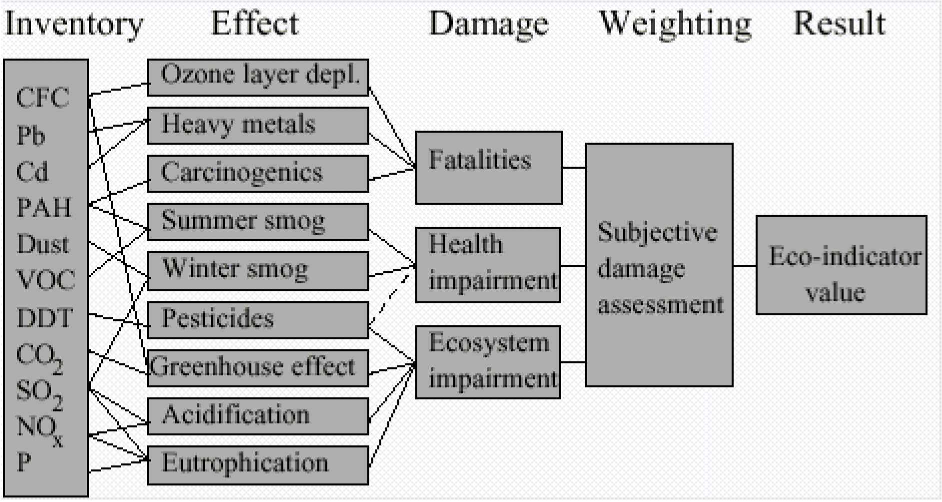


Figure 3.6 Graphical representation of the Eco-indicator 95 methodology [Goedkoop 95a/b]

Other indicator-based methods are:

- EPS, Environmental Priorities Strategy, [EPS 93, Ryding et al. 95] Here, the willingness-to-pay for the protection of environmental safeguard subjects (e.g. clean air) is the weighting criterion. EPS-indicators, called ELUs (Environmental Load Units) thus reflect monetary units. EPS results are a single score value.

- MIPS, Material Intensity per Service Unit [Schmidt-Bleek 97, Schmidt-Bleek 98, Schmidt-Bleek et al. 98]
  Here, flows of moved mass (e.g. abiotic material (e.g. stones), water and air masses) are accounted over the product life cycle. The concept of “Environmental Rucksacks” is developed. It relates to the fact, that for instance materials extraction requires the physical moving of huge masses in order to obtain a certain much smaller amount of refined material. The additional mass that is moved represents a “Rucksack”. MIPS results lead to up to five scores per product, depending on which types of mass flows are considered.

Although the application of indicator-based methods is similar, their background and environmental understanding can vary a lot and so can the presentation of their result.

3.4.3 Product families

An approach being developed in Denmark consists in defining so-called Product families [Lenau et al. 00, Hauschild et al. 99]. A product family, here, is defined as a group of products which are so similar in their environmental characteristics that environmental design recommendations can be given for the group as a whole, while still being specific and detailed enough to be of real value for the development of the individual products within the product family.

3.5 Data for Environmental Assessments

3.5.1 Qualitative and quantitative data

Generally, one can separate quantitative and qualitative data. While the former type is expressed in figures, for instance emissions of kg CO_2, the latter kind is not quantifiable and may, for instance, be expressed as A to D- rating or as “better than”, “worse than” etc. Formal LCAs require quantitative data for reasons of reproducibility and comparability. In Matrix LCAs, however, also qualitative data can be employed. It is obvious, that comparisons, especially when made by non-experts, need to base on quantitative data only because the better solution can be easily determined by the higher or lower value.

3.5.2 Accessibility and quality of data

Full-scale LCAs require lots of data. Therefore, computer support is inevitable for storage of and access to the data in databases and in order to process these data to obtain ‘as is’ results and to run simulations, which give ‘as-could-be’ results.

The huge amounts of data are data on environmental exchanges of the processes in the product system. Typically, the data comes from various sources, such as books, databases, own measurements or individual specialists. This leads to two groups of implications: Data accessibility and data quality.

Data accessibility

Data accessibility was a major obstacle in LCA in the early years due to the fact that environmental data had not been collected earlier. Today, the exiting pool of general data can be called sufficient for many LCA applications. Now, however, the dissemination of data may be hindered by, for instance, *business secrecy policies* or the lack of *data from non-industrialised countries* (The latter can be important, as such countries have become new markets). In such cases estimates have to be used. Their importance for the overall result has to be checked in a sensitivity analysis. Estimates are an inevitable necessity in environmental assessment. As they can be a subjective influence, which can lead to biased results, it is imperative to explicitly state relevant estimates, such as lifetime and expected use pattern, whenever results are presented.

In order to reduce obstacles introduced by different *data formats*, i.e. the structuring of the information on a certain process, international efforts lead e.g. to the development of the SPOLD data format, see e.g. [SPOLD 99].

Data quality

Data quality covers issues such as time period covered, method of collection (e.g. measured, calculated, estimated), geography (area for which the entire data set is valid), technology, representativeness (for the process considered), sources, subsystems included, energy production models used, calorific values used, cut-off rules used, allocations made and others.

The more of these issues are known, the higher the transparency of the data. Data quality is important for LCAs because the viability of the results depends on the data basis used. Data used in environmental evaluation represent various kinds of data. A categorisation is used in [Wenzel et al. 97], pp. 226 ff.

In general, data *types* can be divided into product-specific, site-specific and general data.

Data *sources* can be:
1. Measurements
2. Calculations (based on mass balances and input data for the specific process)
3. Extrapolations of data of a similar type of process or technology
4. Extrapolation of data of other types of processes or technologies
5. Unknown source or non-qualified estimate

An example of data used in the assessment of a refrigerator produced in Denmark is given in **table 3.4**.

LER200

Data reference

	Data specificity			**Data source type**					**Comments**
Product system and process types	Product-specific	Site-specific	General	1	2	3	4	5	
Production of materials									
Steel		X		x					Supplier Gram
Primary aluminium			x			x			Trade organisation
Plastic			x				x		Trade organisation
Product manufacturing									
Moulding of plastic	x		x	x		x			Gram: Measurements of energy,
Processing of steel	x			x					consumption [a] and emissions [b]
Coating of steel	x			x					carried out by certified laboratory
Use									
Energy consumption	x			x					Continuous measurements on 120
									refrigerators over a period of 1 year
Disposal									
Shredding		X	x	x					Largest scrap dealer in Denmark,
Steel		X	x	x					Danish recovery steelworks

Notes

1) Measurements
2) Computation (from mass balance considerations and input data for the process in question)
3) Extrapolation of data from similar process type or technology
4) Extrapolation of data from different process types or technologies
5) Unknown source or qualified estimate

a) Gram and a regional electricity corporation
b) Danish Environmental Centre, Ltd

Product-specific data:	concern processes specifically handling the LER200
Site-specific data:	concern data from actual sites in the product system of the LER200, but the inventory of process data has not been done specifically for the LER200
General data:	all others

Table 3.4 Excerpt of the data used for the assessment of a refrigerator (LER200 from Gram) [Wenzel et al. 97, table 8.2, p. 47]

Ideally, all data used should be product-specific and measured on site. In this way the data would mirror the actual situation as close to reality as possible. However, this is often neither feasible nor necessary. An evaluation can – especially for first iterations – be based on general data for similar processes or technologies in order to get a rough overview. More specific data are often not necessary until second or third iterations are to be performed. And these more specific data usually only involve those processes, which after the first iteration have been detected as decisive processes in the life cycle of the product.

This practice is generally sufficient for conducting an LCA and, provided an appropriate documentation, also for reviewing it afterwards.

3.5.3 Energy data for environmental evaluations

Electricity production mix

The relation between energy consumption and environmental impact is mainly dependent on two factors:

1. The way of producing (or rather transforming) the energy from its primary form (e.g. crude oil) to its final form (e.g. electricity) and
2. the overall efficiency of producing and delivering this energy.

Concerning the calculation of energy flows within Inventory Analysis, ISO 14040, therefore, recommends to take into account

- the different fuels and electricity sources used,
- the efficiency of conversion and distribution of energy flow as well as
- the inputs and outputs associated with the generation and use of that energy flow, [ISO 14040], p. 7.

For electricity, being the primary source of energy in many kinds of life cycle processes (especially in “use” processes), the way of producing is quite different from country to country. An overview is given by tables on energy production mixes such as **table 3.5** below, which contains figures for Europe.

Country	**% input to system from:**					
	Coal	Oil	Gas	Hydro	Nuclear	Other
Denmark	87.6	3.9	3.7	0.1	-	4.7
France	5.2	1.3	0.7	14.4	78	0.3
Germany	57.1	1.9	6.6	4.1	29.2	1.1
Norway	0.2	-	-	99.6	-	0.2
United Kingdom	52.0	7.1	11.0	1.8	27.7	0.5

Table 3.5 Electricity production mixes of some European countries in 1993 (Gross electricity) [IEA 99]

Efficiency

The overall efficiency of the electricity supply in a country depends not only on the mix of fuels but also on a number of other factors such as own-use by the electricity producer, transmission and distribution losses and imports from neighbouring countries. Taking all factors into account, overall efficiencies of electricity production in Europe are about 30 %, on average, as shown in **table 3.6.** An extreme of 70 % efficiency is reached in Norway. Norwegian electricity production is, thus, usually either excluded or mentioned separately.

Country	Overall efficiency [%]
Denmark	31.0
France	31.1
Germany	29.8
Norway	70.7
United Kingdom	28.0

Table 3.6 Overall efficiency of electricity production mixes of some European countries [APME 98]

Overhead energy

On the operational level, an important factor in energy accounting is overhead energy, i.e. the energy which is used for lighting, heating, air conditioning and the like. Overhead energy can be 75 % in manufacturing of electromechanical products, see case examples in [Wenzel et al. 97]

Process efficiency

Another factor on the operational level is process efficiency. This is about 30% for chip-taking processes, e.g. [Schulz/Schiefer 98].

3.6 Relative and absolute evaluations

LCA results are never absolute, e.g. by saying” This is the environmentally best solution at all”. Results are rather relative, which means that they always only refer to those options, which have been investigated. A typical result can thus be *“This is the best solution out of the four options examined”*.

Generally, one can separate two kinds of data respectively methods: more subjective and more objective ones.

Any absolute evaluation has necessarily to be based on absolute data, i.e. on either measured or calculated data. This data is usually stored in a database. Formal Life Cycle Assessment is a means to make absolute evaluations. The biggest obstacle in this approach is that data has to be available.

In contrast to that, relative evaluations can be based on relative or absolute data. Relative means here an assigning of a figure e.g. between 1 and 5 to a certain product characteristic.

An example is given in Chapter 5 in the form of the “Ecodesign strategy wheel” [Brezet/van Hemel 97]: Here, the “selection of a low-impact material” is mentioned (meaning: in its production!) as a characteristic. When product solutions are compared, an arbitrary value between 1 and 5 can be chosen to characterise the material. One solution may be assigned a 2 another a 4. Seven other characteristics (e.g. “Optimisation of end-of-life system”) are assigned values in the same way.

Such evaluations are quantitative but they rely on arbitrary, relative data and can, thus, not be compared with an LCA result. A similar approach is made by Wimmer [99].

When only relative data is employed, a database is not necessary. This is a/the huge advantage of relative assessments. However, their disadvantage is that, as soon as relative data is involved, results cannot be compared to absolute evaluations.

3.7 Energy as an indicator in environmental evaluations - Is it an adequate metric?

In Chapters 6 and 7, of this thesis a structured method for environmental evaluation in early design is described. This method uses exclusively primary energy consumption as an indicator of environmental consequences in the life cycle of a product solution.

This means that direct chemical aspects are disregarded. This section is dedicated to a critical discussion of this methodological choice.

3.7.1 Definition of primary, secondary and final energy

Primary energy is the energy content of energy carriers that have not yet been subjected to any conversion, compare e.g. [VDI 4600, Baehr 96]. The principal example for a primary energy carrier used in this thesis is crude oil with a primary energy content of about 45 MJ/kg, [Boustead 97].

Secondary energy is the energy content of energy carriers that have been obtained through the conversion of primary energy carriers or other secondary energy carriers. Gasoline would be an example.

Final energy is the energy is the energy content of all primary and secondary energy carriers supplied to consumers, reduced by the non-energy demand, by the conversion losses and, in case of self-generation of electricity or gas through the final user, by the auxiliary energy demand. The principal example for final energy is electricity.

It shall be stressed in this context that energy according to thermodynamics cannot be *consumed* but that it rather only can be *transformed* from one form to another.

An internal combustion engine, for example, does not consume fuel energy but transforms this energy into mechanical and heat energy. Therefore, whenever in this thesis (or in literature) the term “consumption” is used, “transformation” is actually meant.

3.7.2 Energy has global attention

Energy is generally recognised as a main contributor to environmental pollution, especially potential climate change, because today’s global energy production is mainly based on the combustion of fossil fuels, either directly e.g. in passenger cars or indirectly in power plants for electricity production, compare e.g. [Kyoto 99, IEA 99]. In the USA, energy-related activities were the primary sources of anthropogenic greenhouse gas emissions, accounting for 85% of total emissions on a carbon equivalent basis in 1998 [EPA 00]. As a consequence, a number of governments initiated special programmes to reduce environmental impacts related to energy, e.g. “Energy 21” in Denmark [Energy 21], the Energy conservation programme in Japan [ECCJ 99] or the “Energy Star” in the USA. Such special attention is required in industrialised countries because they are responsible for roughly three-quarters of the global energy consumption, while their population in total is only about one-sixth of the global population of just over six billion people.

3.7.3 Environmental impact related to energy

Main contributors to energy-related impacts are the transportation sector, as well as households (heating and lighting) and industry [IEA 99]. Many product LCAs show, that energy, e.g. in the form of electricity consumption, has a major influence on the overall result of the LCA. The main reason for this circumstance is, that the energy required is produced by the combustion of fossil fuels. In these combustion processes, fossil carbon is released, which reacts with oxygen to CO_2 (carbon dioxide).

Together with CH_4 (Methane) and N_2O (nitrous oxide), CO_2 belongs to the three most important of the six gases covered by the Kyoto Protocol of the UNFCCC (United Nations Framework Convention on Climate Change) [Kyoto 99, IEA 99]. (Other important combustion gases are SO_x, NO_x, and CO).

The main problem is that these gases contribute to the man-made Greenhouse effect, i.e. to Global Warming. (This effect, in turn, is feared to lead to not “only” a sea level rise due to partially melting polar caps and expanding water masses but also to an additional serious long-term climate change due to a possible halt of the Gulf Stream. [It is, in fact, the so-called “Oceanic Conveyor Belt”, a stream system which transports water around the globe, which is feared to come to a halt. The Gulf Stream is part of this system, [Disc 00].])

CO_2 is considered to be the most dangerous of the Green house gases mentioned due to its sheer amount released globally, not due to its Global Warming Potential value. (Methane, for instance, has an about 25 times higher GWP than CO_2, [Hauschild/Wenzel 98], p. 14.)

In the industrialised world, energy production is the dominant source of man-made CO_2 emissions, and it is thus the energy-related aspects of the product system which can be expected to contribute to these emissions, [Kyoto 99], [Hauschild/Wenzel 98], p.7.

3.7.4 Cumulated Energy Demand (CED)

The Cumulated Energy Demand (CED) is an approach developed in Germany and documented in a guideline of the German Society of Engineers [CED 97] (Verein Deutscher Ingenieure, VDI. Original term “Kumulierter Energieaufwand, KEA”). The guideline includes an English translation where “KEA” is also used as abbreviation. Common practice in English-written literature is, however, to use CED, see e.g. [Klöpfer 97, Frischknecht 97].

The Cumulated Energy Demand states the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good (product or service) or which may be attributed respectively to it in a causal relation [CED 97], p. 4. The CED of an economic good has to be stated always by all three shares, i.e. the CEDs for production, use and disposal. Example values, however, are very rare in literature.

CED/KEA incorporates elements of formal LCA such as the life cycle perspective, the high level of detail in its approach, models and related calculations. CED is, therefore, mentioned as “*one* possible important characteristic value for an ecological assessment” in the guideline, as it ”allows the evaluation and comparison of products and services with respect to energy criteria” [CED 97].

It is, however, discussed controversially in the research field, to which degree the CED could or should be integrated into LCA, [Klöpfer 97, Frischknecht 97]. Glatzel and Kaschenz [95] argue against its use for environmental evaluations instead of LCA, however, they suggest to use it as an stethoscope for energy diagnosis.

3.7.5 Energy in LCA

Energy has often both a resource and an environmental impact aspect. When 1 kg oil is combusted, both a fossil resource is depleted and an environmental impact is imposed. The position of energy in LCA is, thus, “far from settled” (see [Frischknecht et al. 98]).

They argue that energy should only be accounted as resource consumption and not as an environmental impact, as, for instance, the effects related to 1 kWh electricity produced from nuclear power would not equal the effects due to 1 kWh of electricity produced in a fossil-fired power plant. For the same reason, they disagree with using energy, e.g. the CED (Cumulated Energy Demand, see section above) as a streamlining indicator for environmental impacts.

In this context, it shall be said that energy as such of course does not qualify as an indicator for environmental implication, (disregarding waste heat) (see also [Frischknecht 97]). It is a neutral physical term describing an amount of work related to a certain activity, see e.g. [Baehr 96]; be it as an output of this activity (e.g. exothermic chemical reactions) or an input required to accomplish it (e.g. moving an object [a mass] from one location to another).

Environmental impact, however, *is* related to almost all *processes* of converting energy from one form to another or of extracting energy carriers. Transport, heat production and especially electricity production are examples for this. In today's world, the by far biggest share of electricity production is based on fossil fuels, see **figure 3.7**.

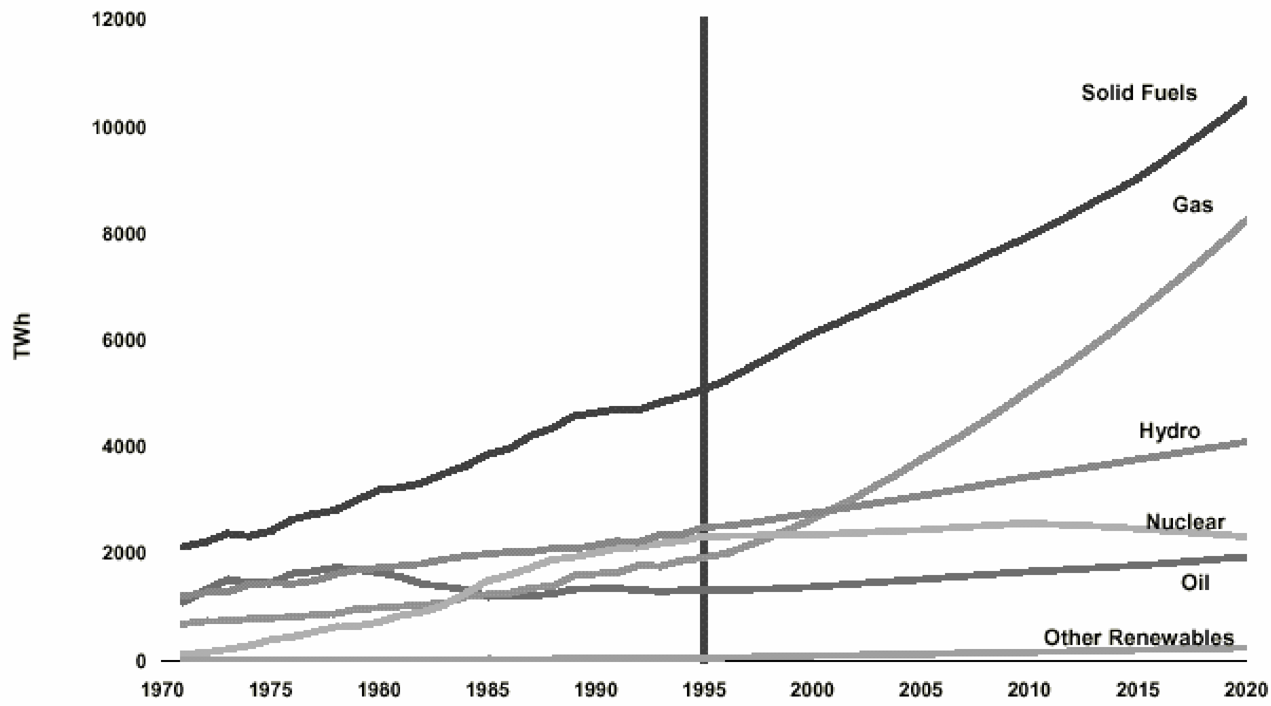


Figure 3.7 World electricity generation by fuel [IEA 98]

If, however, all energy production were based entirely on the exploitation of renewable, i.e. CO_2-neutral, sources, the correlation would no longer exist. This scenario, however, will not be the case in the foreseeable future. So there is in fact a correlation between electricity consumption an environmental impact in today's world.

3.7.6 Chemicals in relation to materials, processes and products

The Oil Point Method described in Chapter 6 is to be used in early product development, in particular in materials and manufacturing process selection. As the OPM only takes primary energy requirements into account, the question arises, whether it is justifiable to disregard chemicals in such a method. The following argumentation deals with this issue.

There is no doubt that chemicals can represent a severe problem in the environment and that they have to be considered when making environmental evaluations. In a full LCA on a refrigerator, for instance, CFCs in the refrigeration system and in the foam of the thermal insulation represented the highest environmental impact of the product. It accounted for 100% of the product’s contribution to Ozone depletion and 75% of the contribution to Global warming, [Wenzel et al. 97], p. 339. Other well-known examples are PVC and bromated flame retarders. Although CFCs and e.g. 1,1,1-trichlorethane are being phased out since the Montreal Protocol (UNEP 93), there are still a lot of hazardous substances around.

The Danish Environmental Protection Agency has compiled a “List of Undesirable Substances” with about 80 hazardous substances that are considered so dangerous that measures either have been taken already, (for instance in the form of EU risk assessments) or where such measures are planned [DEPA 98b]. These substances are listed together with product or material groups, where they are usually applied. Paints, varnishes and adhesives are examples. Plastics (with brominated flame retarders), glasses and textiles are mentioned as well. Also coolants in foundries and substances for metal degreasing, batteries, detergents and cosmetics are mentioned. The list is ordered after the names of the substances. A recompiled list ordered after product groups is given in Appendix III.

The list indicates that chemicals in their relation to materials, processes and products are problematic especially in the function as ancillary substance, e.g. in manufacturing. By far highest weighted environmental impact in manufacturing, however, is very often energy consumption – of manufacturing processes and for overhead processes (lighting etc.). In the life cycle of *mechanical* and *electro-mechanical products* made by these manufacturing processes, chemicals are therefore often not important.

Refrigerators, air-condition systems and other products where the chemical substance fulfils a primary function in the product have to be excepted from this rule, as the example given above shows. Paper can also be seen to belong to this excepted group. It is no mechanical product as such, thus does not involve mechanical design-related materials selection, but it fulfils a major function in many mechanical products, such as regular coffee machines and printers.

Other products where chemicals play a major role are agricultural and food products. But for these products, materials selection usually doesn't take place. And the related packaging is again a mechanical product.

Chemicals often influence the local and regional environment. If the global environment should be chosen to be most important, they could usually be neglected (exception are substances contributing to global environmental impact categories, e.g. CFCs. These are, however, being phased out).

A final point: The impact of chemical substances and mixtures depends on three factors, see [Wenzel et al. 97], p. 23:

- The emitted quantity of the substance
- Its inherent hazard and
- The actual exposure of those parts of the environment that are receptive for the substance and may, thus, be harmed. (The ozone layer is can only be harmed by those emissions of e.g. CFC, which actually reach it)

This is true for emissions to air, water and soil. However, the actual cause-effect chain, especially the actual exposure, is very difficult to model quantitatively, see e.g. [Hauschild/Wenzel 98, Potting 00].

For the above-mentioned reasons, it seems justifiable to omit them from the quantitative part of an environmental evaluation in materials and process selection. Mentioning possible implications of chemicals, however, makes sense. This is done for the OP-indicators listed in Appendix I.

3.8 Requirements upon methods from LCA point of view

In order to be acceptable from an LCA-based point of view, even simplified methods for environmental evaluations have to fulfil the following general requirements:

- The method has to be based on the product life cycle approach, i.e. considering all life cycle stages from raw materials extraction to final disposal.

- The method should employ absolute data rather than relative in order to have a deterministic and transparent basis.

- The method has to be Functional unit-based in order to facilitate comparisons of product solutions.

3.9 Summary & Conclusions

The environment is complex, with many interrelationships, and a major challenge in any LCA study is to isolate the impacts of a single product or service system.

Environmental evaluation can be carried out in an analytical way on one single product or in a comparative way, i.e. for two or more products. Techniques to do so by means of Full LCAs, Screening LCAs and Matrix LCAs have been discussed.

The ISO 14040 framework for formal LCA methods was introduced and it was made clear that especially the Impact Assessment phase of formal LCA can include method-specific choices (e.g. which impact categories are considered and how they are weighted). Comparability between LCA studies is, therefore, also an issue that was mentioned

The MECO principle, structuring LCA work after terminal sources for environmental impacts into Materials, Energy, Chemicals and Others was discussed as well. The question whether energy contemplations alone were a valid metric for environmental evaluations was discussed with the conclusion that it would be sufficient for most mechanical and electromechanical products under today’s conditions for electricity production.

Other conclusions to be made are:

- An environmental evaluation is never fully objective due to subjective influences, mainly through weighting, selection of environmental parameters considered and modelling of the product system.

- It is important to focus on the implementation and integration of LCA into product development processes as e.g. in EDIP. (Existing approaches and paradigms concerning this implementation are discussed in Chapter 5.)

Due to this importance, the following two chapters give an overview over the field of Product Design, which includes Materials and Process Selection, and over tools and methods existing to support environmental design.

4 Material & Process Selection in Product Development & Design

4.1 Introduction

The selection of the appropriate material for a given application and the choice of the best process to shape and join this material have been a problem ever since mankind existed. From Stone Age to Space Age, solving the selection problem was and still is influenced by the materials and processes available and by the set of requirements to be fulfilled in the application, see **figure 4.1**.

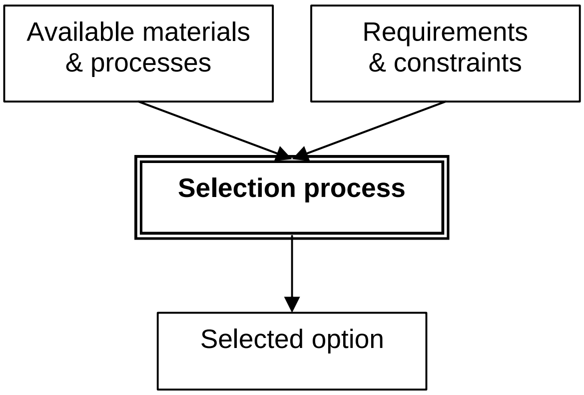


Figure 4.1 Factors influencing the selection process and its result

All factors - available materials & processes and requirements & constraints to fulfil - have increased in number over time, making the selection process more and more complex. Today, between 40,000 and 80,000 materials (see e.g. [Ashby 96], p.1) and a few hundred processes are available. And these numbers are still increasing with technological development. The variety of constraints and requirements has grown as well: Apart from pure functionality and manufacturability, the pre-dominant factor today is cost. Rare situations excepted, a selected solution will only make sense, if it can be produced and sold at a competitive price. Other standard requirements in market economies refer to quality, safety and, nowadays with increasing importance, also environmental compatibility of the selected option. All of these requirements are to a growing extent seen in a life cycle perspective.

Furthermore, the selection problem is usually no longer the basic one of finding a material or process that “does the job” but rather a complicated one where the solution shall be found that “does the job *best*” under the given constraints and requirements.

Starting point for finding a solution will usually be the set of requirements against available materials and processes are checked. It can, however, also be a given material or a preferred process, which is set as a constraint. Product solutions are then sought by employing this particular material or process. Examples for the latter way are products found in Scandinavia where aluminium extrusion was used for many different applications.

Concerning industrial products - being in focus in this thesis (as opposed to agricultural, chemical and other sorts of products) - the selection process usually takes place as part of the product development activity and, in particular, as part of the design activity. The decisions made at the design stage have a substantial influence on the subsequent performance of the product in functional, economical and environmental respect. In order to improve the overall performance of a product it is therefore most effective to influence decision-making at this early stage of the product’s life cycle. This requires an understanding of how Design and Product Development take place. Therefore, this chapter aims to provide an overview over theories, models and methods in Product Design & Development, including those models and methods dedicated to materials and process selection. As this thesis particularly focuses on the selection of engineering materials and manufacturing processes with respect to *environmental* performance, the sections contain comments on whether or not a theory encompasses this issue. The next chapter will then treat environmental design in detail.

In this thesis, two fields are generally distinguished: “Product Development” on the one hand and “Materials & Process Selection in Design” on the other. This distinction is made because Product Development is understood as a more general field while Design and Materials and Process selection (M/P selection) are seen as a special field within Product Development. Another issue is the distinction between Engineering Design and Industrial Design. The subsequent explanations and definitions are given by the author in order to clarify this distinction.

4.1.1 What is ‘Product Development’?

‘Product Development’ is understood as a strategic framework activity. It aims at the successful introduction of products into markets based on the prior identification of customer needs.

Product Development deals with organisational and co-ordination-related activities and touches several disciplines such as marketing, design, production, and (cost-related) controlling.

Ideally, there should be and integration both within each of these disciplines and across disciplines, compare e.g. [Andreasen/Hein 87].

4.1.2 What are 'Design' and 'a designer'?

'Design' is one of the activities within product development (Design can thus be considered a more tactical activity). Design is often understood as "form giving" of a product. However, according to Tjalve [79], its scope also comprises definition of structure, dimension, material and surface of the product (see also section 4.2.5).

Hansen offers this more detailed explanation:

> *"Designing is viewed as a synthesis process in which the product characteristics are gradually determined, i.e. designing can be seen as a chain of decisions. In this process, evaluation of solution alternatives is a means to get insight into attractive areas of the solution space, and decision-making is the activity to determine both the product characteristics and the route of the design process."* [Hansen 99]

Throughout the present thesis, 'design' is understood as the 'activity of defining product characteristics'. Basis for this activity can for instance be market needs (and deducted product tasks) or innovations (e.g. new surface coating processes, which are tried in different applications).

4.1.3 Engineering Design and Industrial Design

The field of Design has both more technical and more esthetical elements. This fact is mirrored by the existence of the two disciplines 'Engineering Design' for the more technical elements (also referred to as 'Design Engineering' or 'Mechanical Design') and 'Industrial Design' for the more esthetical elements. Explanations of Engineering Design being used to define 'inner properties' of products, such as tensile strength and toughness, Industrial Design for 'outer properties', such as 'surface temperature', colour and man/machine relations, are also common.

This demarcation of focal areas can, of course, not be made precisely: Surface properties, for instance, such as hardness and roughness, surely are important issues in both Engineering and Industrial Design (compare also [Tjalve 79] as well as [Seeger 92]). An interesting issue concerning these overlaps is surely also language: While engineering designers refer to 'mass' and 'thermal conductivity', industrial designers will talk about 'weight' and the above mentioned 'surface temperature'.

One also has to notice the differing utilisation of the Design terms in different languages: In American English, the term ‘Product Design’ covers both disciplines, while ‘Industrial Design’ is often used in the (literal) relation to industry as design of industrial structures and processes. In German and Danish language, the term ‘Design’ refers to Industrial Design as opposed to the term ‘Konstruktion’ which relates to Engineering Design. In this thesis, basis is always the meaning in British English given in the above paragraph.

The distinction between Engineering Design and Industrial Design is also based on the differing actors and ways of working in the two disciplines. While Engineering Design is performed by (design) engineers usually working in a more systematic, well-structured way, Industrial Design is performed by industrial designers whose working pattern is more dominated by intuition and creativity. The renowned Danish industrial designer Jacob Jensen, for instance, calls this “looking for lucky shots”, which he uses as starting points for design work, see e.g. [Garsdal 97].

Consequently, complex methods and tools to support designing usually appeal more to engineering designers than to industrial designers. It is important to understand that there are these two groups of actors who have different approaches to the same task, namely to the defining product characteristics.

The discrepancy between Engineering Design and Industrial Design is also obvious in the tool Computer Aided Design: This technology is usually not adapted to the requirements of industrial designers, as creative and intuitive modelling of three dimensional shapes is not supported. The only CAD modelling approach for Industrial Design, known to the author has been made by Lüddemann and Krause, see [Krause et al. 95, Lüddemann 96]. It is in strong analogy with the traditional, in still widely used way of modelling, namely with clay.

4.1.4 What is ‘Materials and Process Selection in Design’?

The selection of materials and processes (M/P selection) is an activity within design. It focuses on the determination of most appropriate engineering materials and manufacturing processes for a component in a given situation. Mechanical and/or other physical targets and economical constraints usually define this situation. Environmental constraints have become an additional focus in recent years.

As the successful development of environmentally improved products depends both on procedures in Product Development and on procedures of M/P selection, approaches to integrate environmental issues exist in both fields. They are described in Chapter 5. As mentioned in Chapter 3 on environmental assessment, environmental implications are usually monitored for whole products in their life cycle. Environmental M/P-selection, thus, has to be done with the whole product and the whole life of this product in mind.

4.2 Theories, Models and Methods in Product Development and Design

4.2.1 Pahl and Beitz

According to Pahl and Beitz, there are three types of design; *original, adaptive and variant design* [Pahl/Beitz 92] (examples from [Ashby 96]:

- *Original design*
  involves elaborating an *original*, i.e. completely new, solution principle for a system (plant, machine or assembly) with the same, a similar or a new task.
  Examples: The ballpoint pen, the compact disc

- *Adaptive design*
  involves *adapting* a known system (the solution principle remaining the same) to a changed task. Here, original designs of parts or assemblies are often called for.
  Example: Carbon fibre composites replacing wood in sports equipment

- *Variant design*
  involves *varying* the size and/or arrangement of certain aspects of the chosen system, the function and solution principle remaining unchanged. No new problems arise as a result of, for example, changes in materials, constraints or technological factors.
  Example: Model planes of balsa wood vs. full-scale planes of aluminium alloys

Pahl and Beitz mention a survey of 1973 in German mechanical engineering industry, which showed a 25% /55% /20% distribution between original, adaptive and variant design activities, respectively, and stress that a good designer has to be creative and flexible.

In short, the three types of design may be termed *novel, refining* and *re-scaling design.* In the context of environmentally conscious design, it is highly important to be aware of the fact that there are these different types of design, as the distinction corresponds with the level of possible improvements that can be achieved.

Pahl and Beitz are renowned for their model of the design process, which is depicted in **figure 4.2**. It describes the steps of how a design task is transformed into a design solution by first making a specification, developing a concept, then a preliminary layout, a definitive layout and a detailed documentation.

In this thesis, the early stages are focused on, i.e. conceptual and embodiment design in Pahl & Beitz's model.

In that model, given in **figure 4.2** the design process involves four main phases:

1. Clarification of the task
2. Conceptual design
3. Embodiment design and
4. Detail design

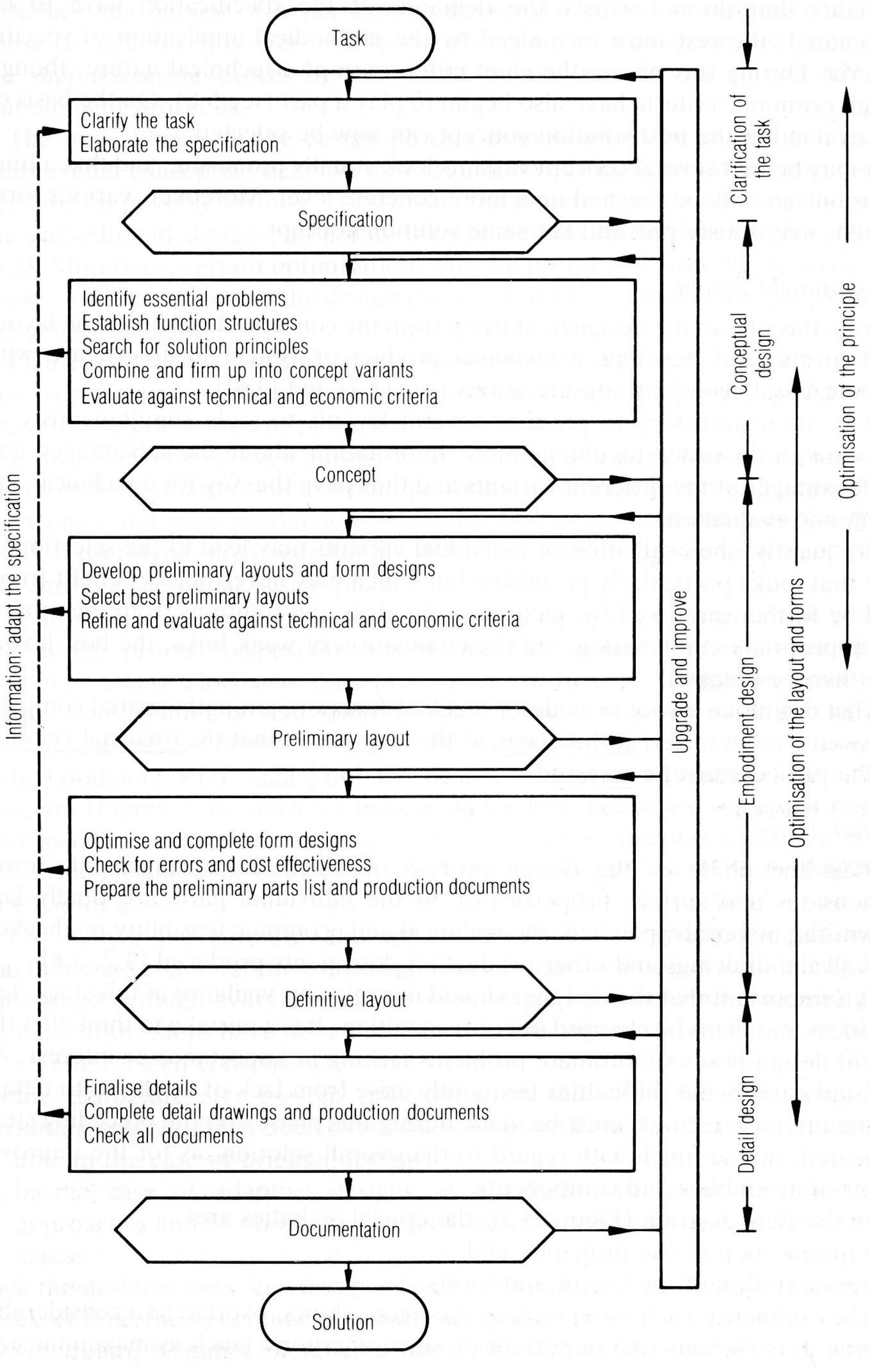


Figure 4.2: Steps of the design process according to Pahl and Beitz. The four main phases of this process - “Clarification of the task”, “Conceptual design”, “Embodiment design” and “Detail design” - are marked vertically on the right-hand side. [Pahl/Beitz 92].

Pahl and Beitz point out the iterative character of the design process by means of the recursive arrows pointing to and away from the vertical bar labelled “upgrade and improve”.

4.2.2 VDI 2221

VDI 2221 is a guideline by the German Society of Engineers, VDI (Verein Deutscher Ingenieure) which describes a systematic approach to the development and design of technical systems and products [VDI 2221].

The model developed for this guideline can be seen as a basis for Pahl & Beitz’s model ([Pahl/Beitz 86], p. 51). It includes two additional steps between ‘preliminary layout’ and ‘definitive layout’.

These steps reflect the modular structure of modern products in prescribing a ‘structuring into modules, which can be realised’ and a ‘design of the main modules’.

Besides the application in mechanical engineering, this model is also adapted for application in process engineering and software development.

4.2.3 Theory of Technical Systems

The Theory of Technical Systems, developed by Hubka and Eder [Hubka/Eder 88], products (being the object of designing) are described as *technical systems* which are part of a transformation system, see **figure 4.3**.

In a transformation system biological objects, material, energy or information can be transformed in a desired way from an existing state (e.g. a tree standing in the forest) to its desired state (e.g. cut and split firewood in a house). The actual transformation is achieved by operators trough a transformation process (all within the transformation system). There are four types of operators which all are more or less complex and therefore systems of their own: human systems, information systems, management & goal systems and, last but not least, technical systems.

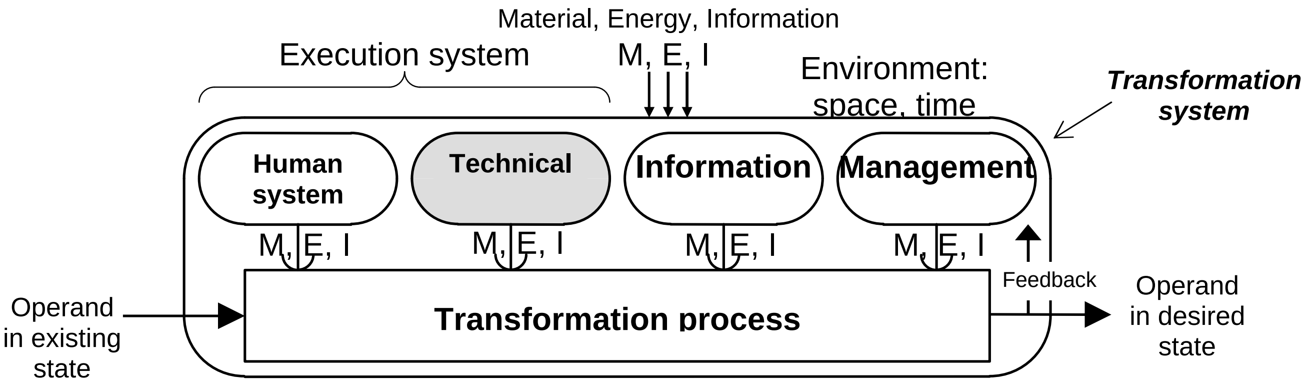


Figure 4.3 Transformation systems, adapted from [Hubka/Eder 88], p. 24 (Operands can be material, energy and information as well as biological objects)

The description of the technical system, i.e. the product, can be done as a set of (technical) sub-systems or components.

The Theory of Technical Systems can be seen as a link between Systems Theory and product modelling. It offers a consistent way to describe product designs and their surrounding systems.

Environmental aspects are covered by the description of the transformation system. This could, in principle, be planet Earth or even the whole universe.

Hubka and Eder mention the linkage between technosphere (encompassing all technical systems) and ecosystems (formed by combinations of geo-, bio- and atmosphere), see [Hubka/Eder 88], pp. 31-32.

4.2.4 Theory of Domains

Andreasen [Andreasen 80] developed the ‘Theory of Domains’. This theory, further on referred to as ‘Domain Theory’, represents a comprehensive integrating means to describe, analyse and - in this way – ‘understand’ products. According to the Domain Theory, a product can be described in four different views or *domains*. These are:

- *Transformation domain,*
- *Function domain,*
- *Organ domain* and
- *Part domain.*

In each domain, the product is understood as a system consisting of elements and relations between the elements.

While the terms “transformation”, “function” and “part” are also found in other theories of design and engineering (e.g. Theory of Technical Systems, see previous section), the term “organ”, introduced in this theory, is rather unique.

An organ is a *‘material area, which realises a function’*. It can consist of one or several parts: For example, the metal part of a screwdriver could be described as a “a torque-transmitting organ”, which realises the function “transmitting of torque (turning moment)” from the handle to the screw. It is an organ, which consists of only one part. A good example for an organ consisting of two or more parts is a pair of scissors. It could be described as a “cutting organ”, realising the function of “cutting” paper. None of the two cutting edges of the pair of scissors could realise this function on its own. Only a movement of one part against the other allows that. (As the movement of the two parts has to happen in a certain way, actually a third part is involved as well: the screw or bolt holding the two parts together)

The utilisation of the term ‘organ’, known from biology, is rather unusual in technical contexts. However, it captures the problem of connecting between the classic areas of function/transformation-related descriptions of a product, as described in the Theory of Technical Systems, (Function respectively Transformation domain) and the similarly classic area of part-related descriptions of a product (Part domain). This connective function, allowing a universal description of a product, is unique for Andreasen’s Domain Theory. (An adaptation of elements of this theory, the “product-environmental property scheme”, is discussed in the next chapter.)

4.2.5 Tjalve (or: Theory of Materialisation)

Contributions to design issues, which are well-established especially in Scandinavia, were made by Tjalve. In his book “A short course in industrial design” [Tjalve 79] (the English version of the Danish original “Systematic Design of Industrial Products” [Tjalve 83]), Tjalve takes a systematic view of the creative process from the original idea of a product to the final and approved design. This process is given in **figure 4.4**. He stresses that the most effective solutions are achieved not by strict systematic work but rather by the right balance between systematics and intuition. Tjalve also puts weight on the continuous alternation between searching for and selecting ideas during the design process.

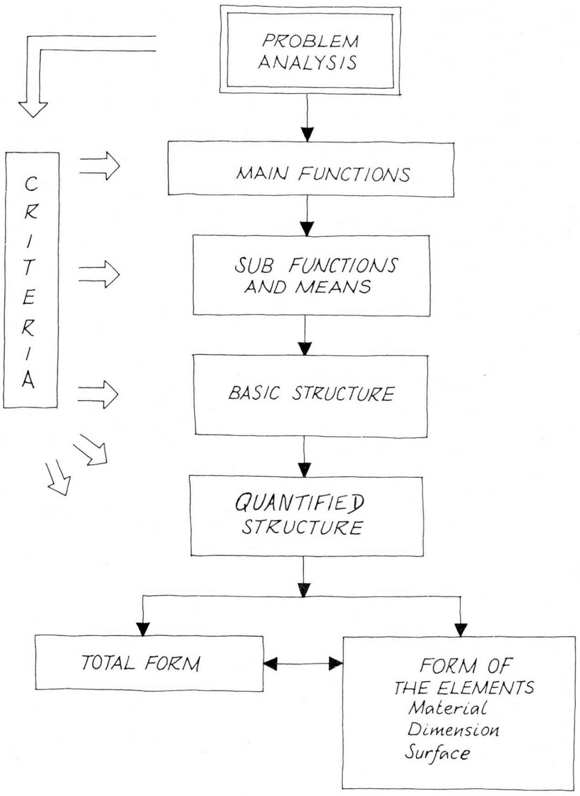


Figure 4.4 A model of the design process showing the stages in the creation of a product [Tjalve 79], p.8

In what has been called by others a ‘theory of materialisation’ or ‘theory of product synthesis’, he defines five fundamental properties: structure, form, material, dimension and surface. These fundamental properties are influenced by a number of product factors (the set of factors from design, production, sales, use, and destruction) stemming from the different stages in the life cycle of a product (**fig 4.5**).

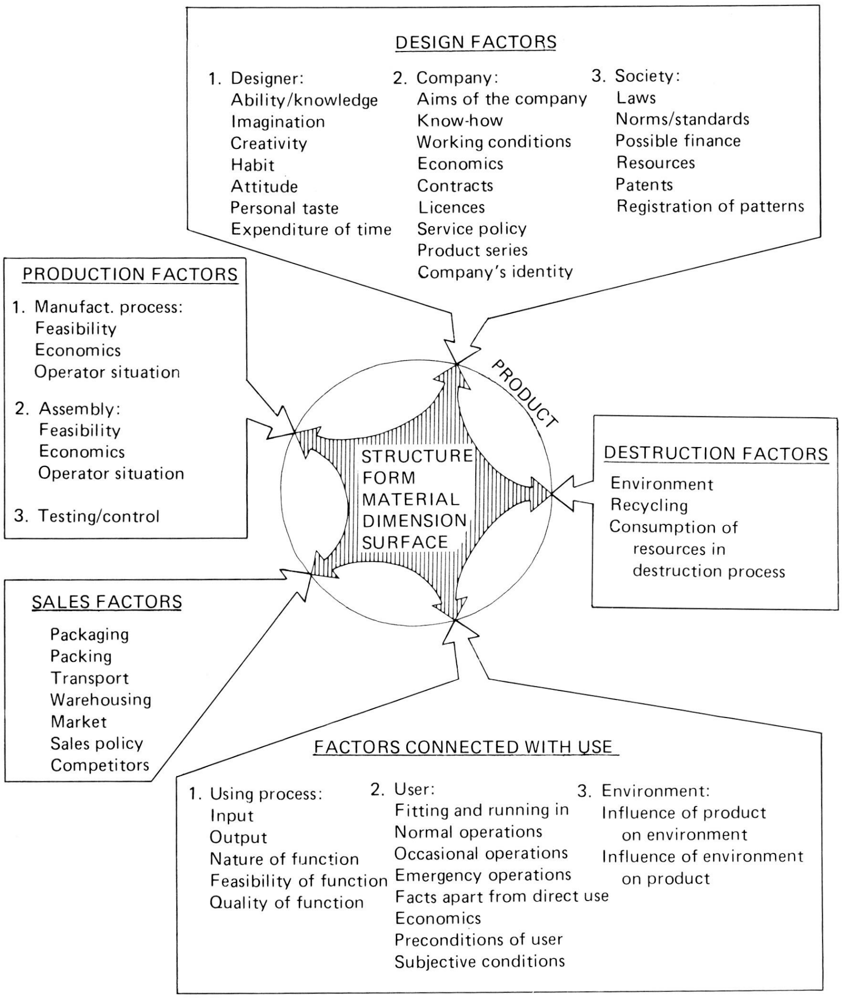


Figure 4.5 Factors influencing the fundamental properties of the product during its life, from [Tjalve 79], p. 96

In this life cycle perspective, environmental issues are specifically mentioned, such as

- resources,
- occupational health ("operator situation"),
- influence of the product on the environment and vice versa as well as
- recycling

Although environmental aspects are not deeper elaborated upon in general, a few short paragraphs on 'use factors' respectively on 'destruction factors' include comments that biodegradable materials may be used and that recycling ought to be considered (see [Tjalve 79], p. 140).

4.2.6 Integrated Product Development

Integrated Product Development is a model for product development, introduced by Andreasen and Hein, which circumscribes the idea to integrate market-, product- and production-oriented development activities in companies rather than to keep them separated, see [Andreasen/Hein 87]. The model therefore outlines a sequence of parallel, interrelated activities all leading from a need for e.g. a new product to successful business for the company, see **figure 4.6**.

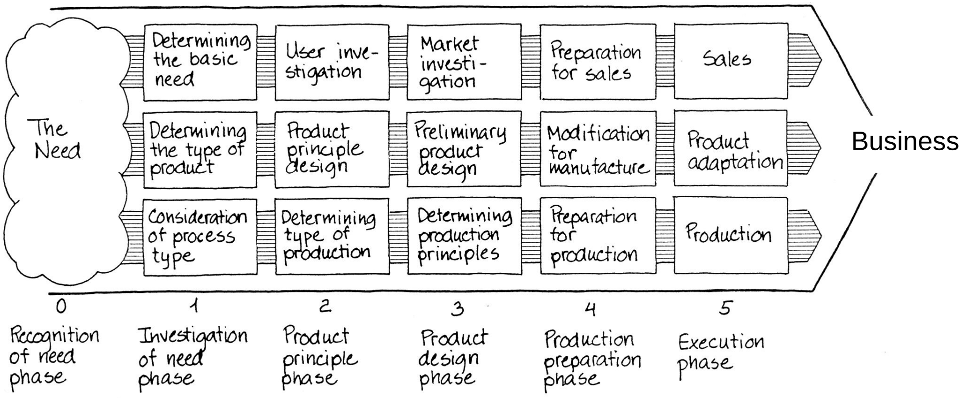


Figure 4.6 The model of Integrated Product Development [Andreasen/Hein 87], p. 27 (term ‘business’ added according to fig. on p. 22 of the source)

Within this large context, the choice of materials and production techniques can be seen as shared activities between, which involve iteration circles.

4.2.7 Two comments

It is a great leap from describing a product to designing one, especially an environmentally optimised one. There are two principal reasons:

1. In order to perform environmentally conscious design, designers require methods.

The *theories* mentioned earlier are means to *describe* products in various ways by means of models e.g. of the product itself and its surrounding systems. Theories provide two crucial things - a ‘language’ for designers to communicate in and a ‘framework’ for their work. This work, i.e. the actual procedure of designing, is described in *models of the design process*. With basis on theory and design process models, a third element in design science are design *methods*. Methods prescribe procedures of how to accomplish goals. Methods for environmentally conscious design, for instance, prescribe the procedure of how to design a product at hand in such a way that the product has a minimum potential impact on the environment. Methods can be used by experienced designers in the same way as by inexperienced ones, but they are probably most valuable to the latter group.

As environmentally conscious design is a relatively new discipline and designers' experience in the field therefore limited, especially *methods* are, therefore, asked for by environmentally conscious designers. (The following chapter is devoted to this issue.)

2. A product description is unambiguous; the way to reach a product description is not.

The ways of designing described here are structured sequences where the different steps are known. Experience shows this, despite the fact that the actual result – a detailed product design - of the same sequence performed by different groups of people will probably be quite different. This is a generic circumstance – not a problem. One reason for this circumstance is that decisions in design are influenced by subjective, individual influences, which can be termed as the underlying 'mindset'. This means that there is never "the one, correct" way of getting to a product design but rather that there is always a variety of equally feasible ways.

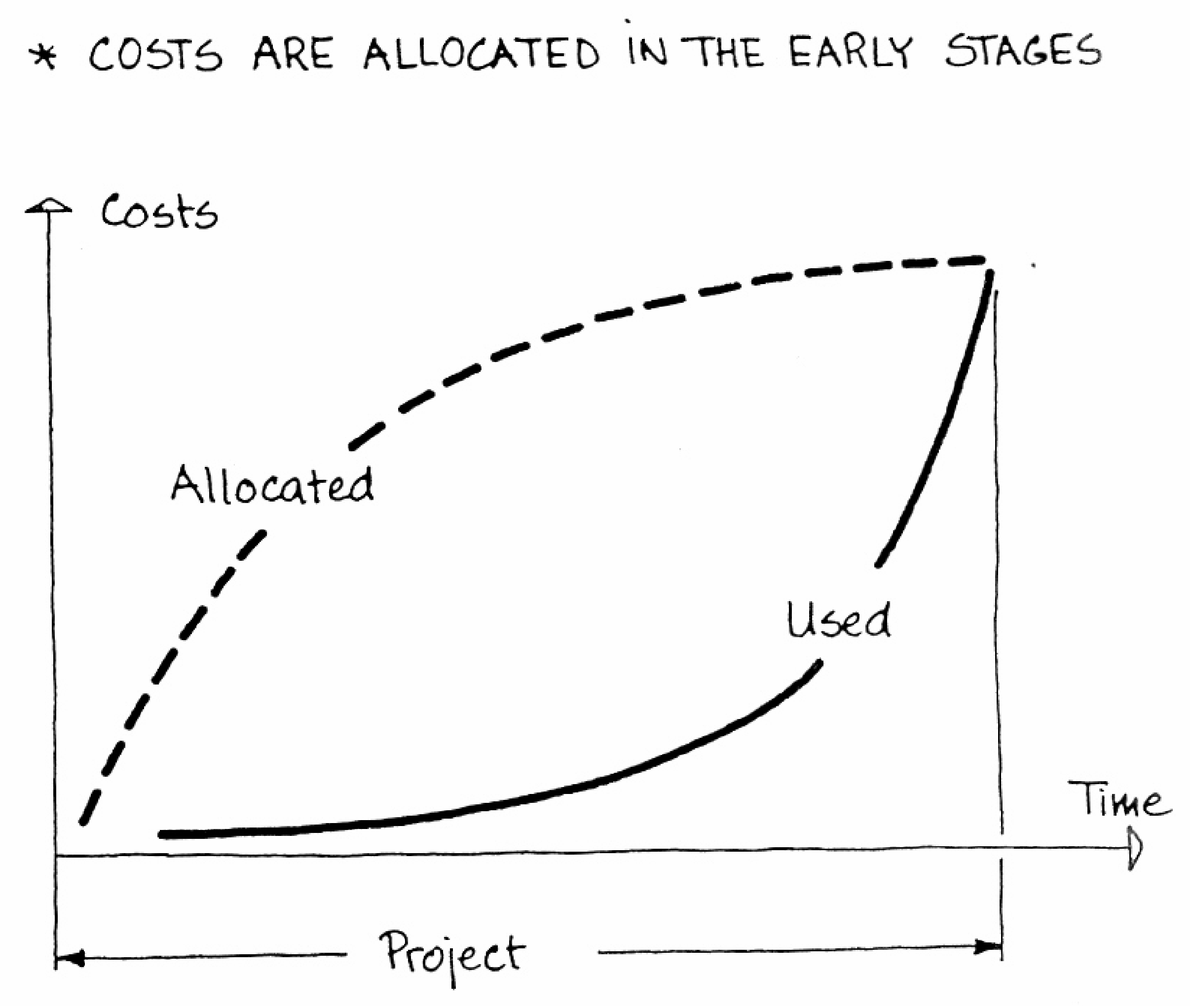


Figure 4.7 Andreasen & Heun also stress the importance of decisions in the early stages of a development project because a great share of the overall costs are allocated very early in the process [Andreasen/Hein 87]

4.2.8 Definition of product concept

Considering the different explanations described so far in this thesis, a product concept shall be defined in the following way:

> "A product concept is a description of a product in terms of the working principle employed to fulfil the main function of the product and in terms of possible physical solutions to realise the working principle, including candidate materials."

Despite some discrepancies with the models and theories described above (e.g. Pahl & Beitz don't include candidate materials in their definition of a concept [Pahl/Beitz 92], p. 40), this definition is formulated in order to give a common understanding of the term "product concept" for the later sections of this thesis. The definition is inspired by typical use of the term "concept" in common language. The term "concept car" is such an example, which fits to the definition by the author but not to e.g. Pahl & Beitz's terminology.

4.3 Selection of Materials & Processes

4.3.1 General constraints in M/P selection

There are a couple of general constraints, which affect any M/P selection:

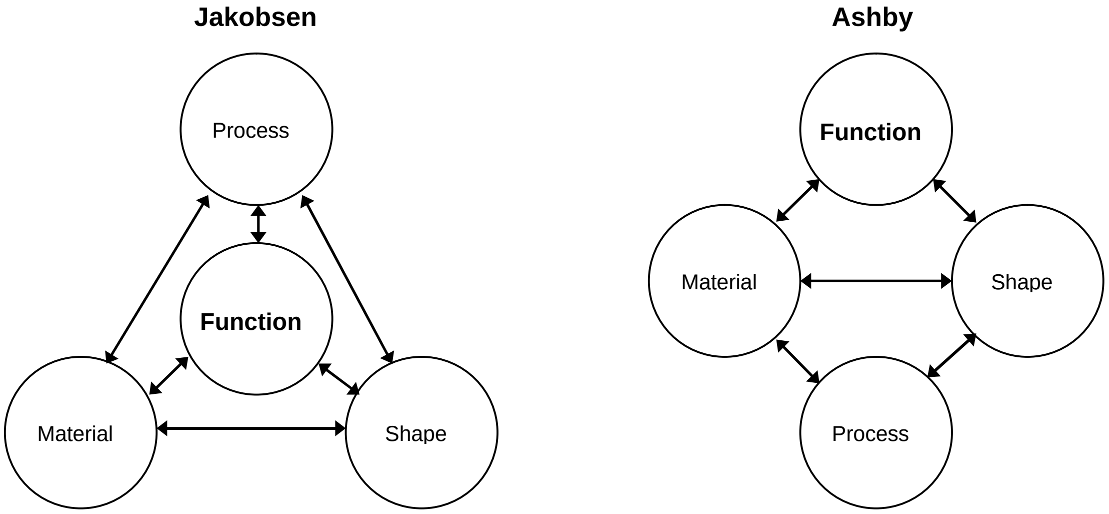
- Interdependence of function, material, process and shape

Products are designed to fulfil a function. Whenever candidate materials are examined, feasible manufacturing processes (or rather: chains of manufacturing processes) have to exist to shape the material in the desired form and to join parts made of the material.

On the other hand, manufacturing processes are often limited to certain material groups or shapes and limit in that way the solution space for the designer.

Jakobsen sees 'function' in the centre of an interrelation of all factors with each other [Jakobsen 89], whereas Ashby leaves out the 'process'-'function' interrelation [Ashby 96] as the process is independent of the function of the product and the function is not dependant on the process as such but on its outcome, e.g. a shaped material, see **figure 4.8**.

Figure 4.8 The interrelation between function, material, process/production method and shape according to Jakobsen [89] (left) and Ashby [96] (right).



- Materials and Process Selection usually involves finding candidate materials and comparing them based on a variety of properties. This means that M/P selection often involves trade-off situations.

- Each M/P selection is a compromise! Besides environmental implications, which are in focus here, there are always several other parameters to consider (economic, manufacturing-related, etc.), which often even may be contradictory. (See, for instance, figure 4.5 of Tjalve again.)

- M/P selection can be done objectively on the basis of physical properties.

- Generally valid assertions about the environmental performance of materials – such as: *“Wood is always preferable compared to plastics!”* - are not possible. As will be elaborated in the next chapter, the reason for this circumstance is, that environmental performance is determined by interactions of the product as a whole during its life cycle

- With respect to processes, generally valid assertions are possible. A process which, for instance uses less electricity for a unit operation, say one meter welding, is indeed practically always environmentally preferable. A reason for this is that seen in the *product* life cycle perspective, the processes during manufacturing usually are of minor importance.

Materials selection and process selection are not clearly separable from each other. Therefore, Lenau [96-00] suggests to approach the problem from both material, process and product perspective. In his Internet application "Design inSite", designers are provided with key information on processes and materials and example products show commercial applications. In this way, designers are informed and inspired at the same time.

There are, however, authors and research groups that either focus more on materials or processes. Compared to each other, more researchers are involved in materials selection than in process selection. The following sections summarise main recognitions.

4.3.2 Methods with focus on Materials Selection

4.3.2.1 Budinski

In "Engineering Materials - Properties and Selection" [Budinski 92], Budinski gives a very comprehensive introduction to properties of metals, polymers, ceramics and composites. A short section treats recycling of plastics. Special chapters cover different kinds of steels and steel alloys, copper and aluminium alloys, corrosion and powder metallurgy. Manufacturing processes are often described by means of figures of the manufacturing steps involved. Only one chapter - of all in all 21 chapters - covers "The selection process".

According to Budinski, the selection of materials takes place at the end of the design process, which is depicted on **figure 4.9**. He mentions part respectively component design as the focus of his approach, rather than product design.

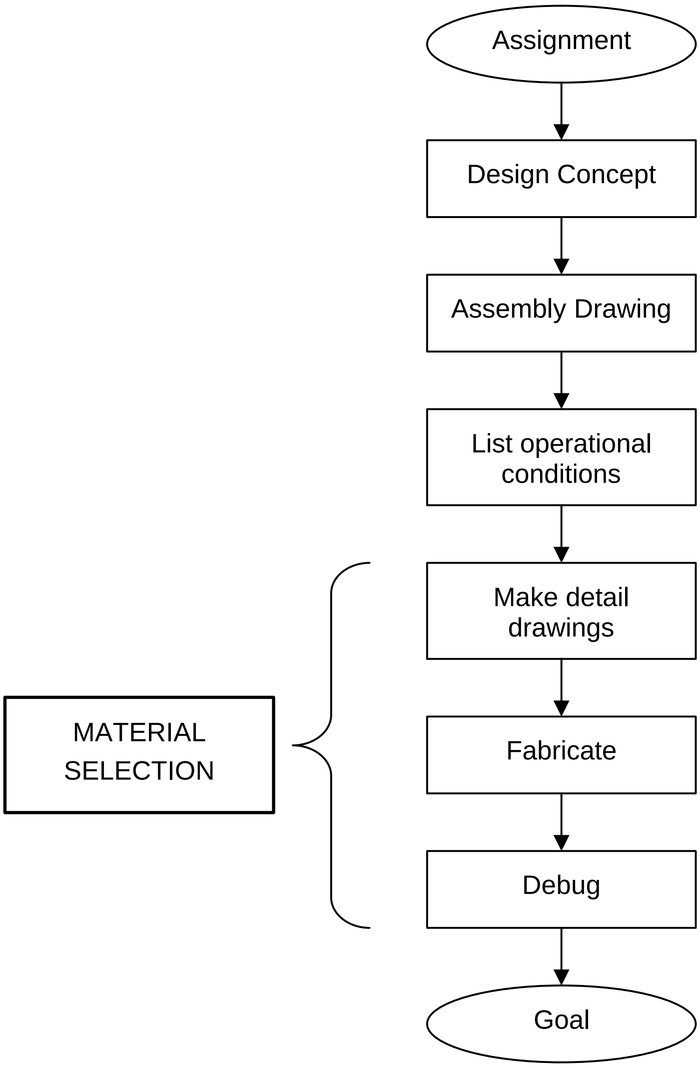


Figure 4.9 The role of Materials Selection in the design process, adapted and simplified from [Budinski 92], p. 649

As the three main selection factors he mentions

- *Properties* (mechanical, physical, etc.),
- *Availability* (on hand, order from warehouse, special processing required, etc.) and
- *Economics* (raw material price, quantity required, etc.).

For each design task, a set of a few specific *important selection factors* has to be defined by the designer. The decision on the material then has to be based only on these factors, e.g. corrosion resistance, a certain hardness value or the like. Finding these important selection factors is, however, difficult, as further methodological assistance is not given.

The book can be recommended to individuals interested in subjects like materials sciences, the production of materials from raw materials and the various properties of materials. When looking for methodological aid in materials selection, however, the book is not a very helpful source. This is because the procedure described involves considerably much experience e.g. for defining the relative importance of Budinski's three main selection factors properties, availability and economics.

4.3.2.2 Ashby

The method developed by Ashby is based on graphical "Selection Charts". These charts are available as printed matter (see **fig. 4.10**) but also implemented in a computer tool, the Cambridge Engineering Selector. (Ashby also developed a method for the selection of manufacturing processes, see next section).

In the book, "Materials Selection in Mechanical Design" [Ashby 96], Ashby describes and discusses, among other things,

- the design process as such,
- engineering materials and their properties,
- the development and use of Material Selection Charts (see **fig. 4.10**), as well as
- Process Selection

He also covers data sources and their use as well as aspects of materials, aesthetics and industrial design. Selection charts, mechanical and physical formulae, case studies and useful approximate solutions for standard problems are provided, too.

Environmental aspects are included in the method in two ways:

1. Influences of the environment on the material (these could be called "passive environmental influences") and

2. Influences of the material on the environment (these may be called “active environmental influences” and are in focus in this thesis)

He suggests using energy content as a way to consider environmental pollution related to the production of materials because it is easier to quantify than other forms of pollution. The next chapter provides more on information on environmental concern reflected in Ashby’s method.

Ashby’s selection method always has the complete range of materials as a starting point. Two steps are then separated:

Screening - where materials are separated, which fulfil the requirements of the selection problem (they are capable of “doing the job”) followed by

Ranking - where the material is determined, which “does the job best” (The steps screening and ranking can be performed several times)

The core in this method are Materials Selection Charts. These charts use the principle of plotting different (single or compound) properties of materials against each other (figure 4.10).

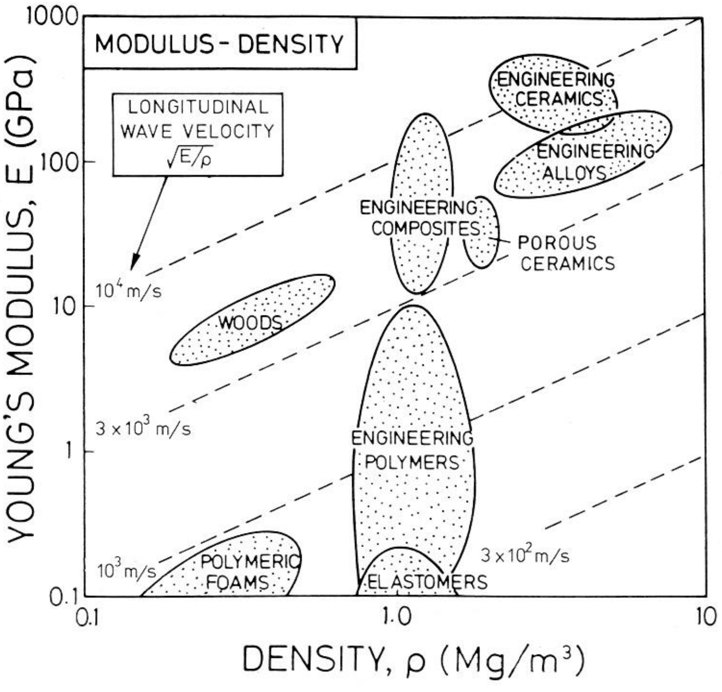


Figure 4.10 A materials selection chart showing Young’s modulus against Density, both on logarithmic scales. A third property, which depends on both Young’s modulus and Density, is the Longitudinal Wave Velocity. Constant values of this property are plotted as straight lines into the selection chart [Ashby 96], p. 25

The axes on the selection charts are usually chosen to have a log-scale. This allows third properties, which are only dependent on the two properties that form the axes, to be plotted as straight lines onto the selection chart. In the same way, compound properties, so-called *Performance Indices,* can be plotted into the chart as straight lines.

Application

The user of the method has to define the selection problem itself (by defining the function of the component and the objective of the optimisation) and additional constraints in physical/ mechanical terms. An example could be *“A material for a beam (length, height and width are given) which is loaded in bending with a given load F, and the constraints that the deflection must not be more than a given value and that the beam should be as light as possible”*. With a description like this and some mechanical formulae, an appropriate material can be found in the respective selection chart(s).

Advantages

A clear strength of the method is that it leads to objective selection results as it is purely based on objective data, formulae and correlations. Materials can, thus, be compared in an objective way.

Also, when aiming at finding innovative solutions, Ashby’s way of using all classes of materials as a basis is clearly the best way to find all possible solutions for a given problem that can be described in mechanical terms. In a small case study by the author on materials for window frames, for instance, the method resulted in suggestion not only for wood or plastic but also for foam aluminium, which initially hadn’t been thought of as a possible option.

Drawback

The main drawback of the method, especially from a non-engineer’s point of view, will be that requirements upon the material have to be expressed in technical terms like e.g. plain physical quantities. This is necessary because such technical terms are used as the axes of the selection charts (see **fig. 4.10** again) and for Performance Indices. The problem is that it may be difficult to decide which is the main parameter to optimise, especially in trade-off situations (, which unfortunately are typical in materials selection). Moreover, individuals who do not have a basic education in physics or mechanics, e.g. industrial designers, will have difficulties to use the method at all.

For engineers with general knowledge in mechanics, aid is provided in the form of various case studies and additional helpful booklets.

The software tool “Cambridge Engineering Selector (CES) [CES 99]” (formerly called “Cambridge Materials Selector (CMS) [CMS 97]) is very comprehensive and comprises a range of modules. The data resources in CES cover - among other things - the whole range of materials in great detail and belong undoubtedly to best on the market. See Chapter 6 for details.

Specific related work exists on the mechanical performance and selection of natural materials, see [Wegst 96]. (Further information can be obtained from Internet sites of the Department of Engineering of Cambridge University and from Granta Design Ltd. for the CES software, see Appendix IV).

4.3.3 Methods with focus on Process Selection

In contrast to knowledge on materials, which is available in many data books, knowledge on processes supporting their selection is available to a limited extent. Allen/Alting [86], Kalpakjian [84], Bralla [86] are exceptions.

An issue of general importance in process selection is that not single processes but rather *process chains* are selected, e.g. [Lenau 90]. Sheng and Worhach [97] discuss process chains in relation to Design for Environment.

Whenever a material or process is to be selected, it is very helpful to know how big the theoretical solution space is. Therefore, Haudrum suggests using matrices where possible material and manufacturing process relations are given [Haudrum 94]. For each reasonable combination, the designer can then try to generate solutions.

Energy consumption and resource consumption of processes is stressed by Jepsen [78] as a selection parameter. He also mentions “Job satisfaction, Working environment and External environment” as influencing parameters.

Esawi [94] developed a systematic method for process selection based on Ashby’s concept of screening and ranking during the selection process.

4.4 Summary

A main point to remember from this chapter is that Product Development is a more strategic framework for design activities, whereas materials and process selection is a rather tactical but central activity within design. While product development works on the “product” level of design, M/P selection focuses on the “part/component” level.

The main design process model is that of Pahl & Beitz. The importance of the early stages in the design process has been explained. The term “concept” as often used in early design has been defined as it is understood in this thesis.

Methods and models for materials and process selection have been discussed and the strong relation between process, material, shape and function has been pointed out. The necessity of making trade-offs in design has also been shown, as design often involves multi-dimensional optimisation.

A material selection process can either have a set of requirements as a starting point, which is the usual case, or begin with a material, which has to be shaped or modified in such a way that it fits to the requirements. In both ways, innovative component or product solutions can be found.

5 Tools & Methods for Environmental Product Development and Design

5.1 Introduction

The overall issue in this thesis is the integration of environmental aspects into the design process, especially during the process of selecting materials and manufacturing processes within product design. The central questions are here in which way this can be done at all and what the most effective way to integrate it into material and process selection would be.

This chapter, therefore, discusses existing methods and tools to answering these questions. In order to explain overall conditions for these methods and tools, four subjects are discussed in the beginning:

- constraints in companies,
- terminology,
- the environmental design process and
- information requirements in early design

Approaches in product development in general and in the selection of materials and processes in particular will be discussed. Based on the findings of the previous chapters, these existing approaches will be discussed.

5.2 Constraints for practising environmental design in companies

5.2.1 Pro-active, receptive and reactive attitude

The general attitude of a company can be categorised into (compare [Olesen et al. 96, Fiksel 93, Fiksel 96, Graedel/Allenby 95])

- Reactive/ passive,
- Receptive and
- Pro-Active

Passive attitude

A ‘reactive’ or ‘passive’ company is more or less closed towards signals from and developments in its surroundings. It changes policy or increases efforts only when being forced by concrete legal or societal requirements.

Receptive attitude

A ‘receptive’ company is generally open towards signals from the surroundings. It strives to foresee future developments and related possible requirements and tries to react before concrete requirements become reality.

Pro-active attitude

A ‘pro-active’ company is not only open for external signals but takes them up as a challenge, which can lead to an enforced position in the market. It, thus, may even start initiatives out of own motivation, e.g. in the form of proposals for new standards.

The conditions to perform environmental design are obviously best in ‘pro-active’ companies. However, even ‘passive’ companies need some environmental data in order to document their performance. Especially ‘passive’ companies will appreciate, if the effort to quantify and document environmental performance is low. This is an argument for simplified approaches.

5.2.2 Activities on organisational and operational level

In order to reach improvements in the environmental performance of products, environmental issues should be treated as an integrated part of company strategy and product design processes. Both are company-internal factors. (Another crucial but company-external factor to reach product-related environmental improvement, namely the behaviour of the user, shall be set aside for the moment.)

Putting environmental design into practice in companies, thus, has to take place on two general levels:

1. The organisational level
2. The operational level

Organisational level

At the organisational level, there should be an adequately defined frame. Such an organisational frame may, for instance, include

- a set of environmental targets defined by the board of management and
- a company-specific “environmental mind-set”, i.e. a definition of what is considered to be the main parameters characterising the Environment for the particular company.

Installing an environmental management system is another appropriate means. Established standards in this field are ISO 14000 ff. [ISO 14001] and the British Standard BS 7750 [BS 7750].

Companies certified after these standards can, furthermore, participate in the European Environmental Management and Audit Scheme (EMAS) [EMAS 93].

Operational level

At the operational level, evaluation methods applicable during the product design process are the means of putting environmental design into practice. Here, focus is on individual designers and design teams that shall be able to make environmentally conscious decisions.

The following sections deal with the latter, operational aspect of putting environmental design into practice.

5.2.3 Individual designers and design teams

In principle, environmental design, just as design work in general, can be performed in two ways:

1. By a design team consisting of specialists of various fields including one or more environmental specialist or

2. By an individual designer who has qualifications in various fields including environmental issues.

The first situation is usually found in larger firms, while the second one can be assumed to be standard in smaller or medium-sized enterprises.

Estimating that in Western industrial societies a large share of the Gross National Product (GNP) is produced by small and medium-sized enterprises (SMEs), it seems appropriate to focus on single designers, rather than on design teams. (However, these SMEs often produce parts or sub-assemblies for more complex products produced by large companies. And specifications on the parts, e.g. concerning materials, are thus usually defined by these larger companies.)

The strongest argument for focussing on individual designers is, however, the fact that methods tailored for them, of course, also fit to design team tasks, whereas methods requiring an LCA specialist do not. (The “Product family” approach, see 3.4.3, is an exception as it requires LCA specialists but produces results for single designers.)

5.2.4 Designers and environmental design

The group of people involved in Life Cycle Design is often referred to as “designers”. It is most often not specified who precisely is meant with the term. A distinction between, for instance, industrial designers and engineering designers is hardly ever stated.

Life Cycle Design (LCD) as an activity within product development usually involves industrial designers, engineering designers, architects, environmental specialists, economists, marketing people, managers and, of course, the customers, compare [Andreasen/Hein 87]. This means that Life Cycle Design addresses a very *heterogeneous* audience.

In order to practise LCD, a certain degree of environmental understanding is required. Apart from the environmental specialists, however, all other involved parties usually do not have specific knowledge in the field of environmental evaluation. With respect to their professional background - and thus their way of practising LCD - all involved parties may be divided into two groups:

- one group with a more technical background and a more structured way of working (engineering designers, some architects, environmental specialists, economists, managers)
- and another group with a more artistic-creative background and a more intuitive way of working (industrial designers, some architects)

Many methods and tools addressing Life Cycle Design, however, require a considerable degree of environmental understanding or are not appropriate for intuitive, pragmatic working in design. The latter circumstance is, for instance, stressed by Bakker ([Bakker 95], p. 86) who conducted empirical investigations in the field of environmental information for industrial designers (see also [Smets/Overbeek 94]).

In the context of this report, the term “designers” will be used, covering people conducting product development *who do not have specific knowledge in environmental evaluation.*

5.3 Terminology and approaches in Environmental Design

“Excellent (environmental) design is the opposite of fashion and of programmed obsolescence.” This elegant definition for environmental design was given by the curator of an exhibition on environmentally designed products in Germany, see [LS 97]. “But what is environmental design actually and how is it *performed*, i.e. what methods and techniques exist?”, one may ask. Other questions arising are: “What is the difference between the different terms used in the environmental design field? Or do they all mean more or less the same?” The subsequent sections aim at answering these questions.

The number of terms used in the field of environmental design is almost as diverse as the understanding of the term “environment”. In literature, activities in Product Development and Design which are specifically focused on environmental compatibility of the product are referred to under the following terms (incl. related manufacturing terms):

- Green Design/Green Manufacturing,
- Eco-design (Ecodesign, Ecological Design)
- Life Cycle Design,
- Design for Environment (DFE) and related DFXs,
- Environmentally Conscious Design (ECD)/Environmentally Conscious Manufacturing (ECM) and sometimes
- Environmentally Benign Design
- Sustainable Design, Sustainable Product Design

Terms often used synonymously

There exist no commonly accepted definitions for most of these terms as to what they cover, how they differ from each other or which specific aspects they have in common besides the general environmental focus. The terms are, therefore, often used synonymously. The bandwidth of what is meant with the different terms is, however, very wide, as will be shown later. In fact, this is even true for the term *Environment* as such (see Chapter 2).

In order to find answers on the questions stated at the beginning of this section, the following paragraphs provide an overview of explanations found in literature and a subsequent suggestion to structure them:

Green Manufacturing/Design

According to the American Society of Manufacturing Engineers, ASME, Green Manufacturing is "*the intersection of manufacturing product and process practices with environmental issues and concern. The greater the overlap between these areas, the greater the extent to which manufacturing practices recognise and embody environmental issues, concerns and practices.*", [Melnyk/Smith 96]. Graedel and Allenby of American AT&T utilise expressions such as "Green accounting" [Graedel/Allenby 95] p.87.

Design for X

Design for X covers all "Design for "-approaches, such as "Design for Manufacturing" and "Design for Assembly" and the like. Environment-related DFX terms are *Design for Recycling, Design for Disassembly, Design for Re-use,* etc. and *Design for Environment (DFE).* Design for Recycling is described in a guideline of the German Society of Engineers (Verein Deutscher Ingenieure, VDI) The guideline states that "*… in a recycling-oriented design process, especially those steps are important, where the designer makes decisions, which influence:*

- *production waste,*
- *lifetime of the components,*
- *joining techniques and*
- *material combinations*" [VDI 2243], p. 8.

Most terms belonging to the group of DFE-related terms are self-explaining. DFE itself is defined in a Danish contribution as “*a tool in product development, which includes techniques and procedures for environmental analysis, diagnosis, goal setting, focussing, solution exploration and verification.*

All together under the premise of improving the environmental properties of mechanical and electromechanical products.” [Olesen et al. 96], p. 8. Fiksel (from the USA) defines DFE as “ .. *systematic consideration, during new product and process development, of design issues associated with environmental and human health and safety over the whole product life cycle.”* ([Fiksel 93], p. 126].

Other definitions of DFE can for instance be found in [McAloone 98] and [Mackenzie 97] (The latter author uses Green Design and DFE as synonyms even in the title of her book). Graedel and Allenby consider DFE as the implementation of their vision of Industrial Ecology in industry [Graedel/Allenby 95].

Eco-design/EcoDesign
In a Dutch contribution, the term *Eco-design* is understood as *“the integration of environmental aspects into the familiar product development process”* [Brezet/van Hemel 97]. According to a contribution from the UK, Eco-design *“is the design of a product, system or service with the aim of minimising the overall impact on the environment. Performance, quality and value should not be compromised by design.”* [Simon et al. 98].

Life Cycle Design (LCD)
According to a Danish contribution, *Life Cycle Design* means that *“… all life-cycle phases (design, production, distribution, usage and disposal/recycling) are considered from the beginning of the conceptual stage to ensure fulfilment of the environmental requirements”* [Alting 93].

A comparable definition can be found in a German book on Life Cycle Design [Behrendt et al. 97], p. 21: *“Life Cycle Design is the products and processes that encompasses the entire life cycel of a procust: from raw material extraction and processing to the production, distribution, use and return of materials to the industrial cycle or their disposal. The main objectives are to prevent and reduce material and energy input, material diversity and the use of hazardous substances. Life Cycle Design is based on the fundamental assumption that these measures will decrease the burden on the environment.”*

Sustainable Design/Sustainable Product Design (SPD)
The most wide-spanning term is *Sustainable (Product) Design,* which covers *all* aspects of Sustainability (see e.g. [Alting 95]). SPD includes not only environmental aspects but also economical and social/societal ones.

It builds on the concept of Sustainability (, saying that a sustainable development allows the present generations to fulfil their needs without compromising future generation in fulfilling theirs, see Chapter 2). Charter and Chick state [Charter/Chick 97]: "*The key aspect of Sustainable Product Design (SPD) is the addition and balancing of social and ethical issues, alongside with environmental and economic issues into the product design process to achieve the 'quadruple bottom-line'*". As the aim for Sustainable Design, reductions in resource and energy consumption of a factor between four and ten are stated by the authors as well. (This so-called "factor discussion" is treated in Chapter 2.)

Country-specific utilisation

There seems to exist a pattern of country-specific uniform utilisation of a term: Sources from the UK often use "environmentally-conscious" or "environmentally-benign design", US sources often use "Green" as a prefix while Dutch sources seem to prefer "Eco" instead. German and Scandinavian sources often utilise "Life Cycle Design (LCD)" and "Environmental Design". Disproving examples are, however, always there. Apparently, the only commonly used term is "Design for Environment (DFE)". Finally, it may be stated that the term "EcoDesign" seems to become generally utilised for all approaches, which employ formal or simplified LCA methods in the design process.

Charter and Chick also introduce a so-called "four steps" model (**fig. 5.1**) which describes steps and strategies to Sustainable Product Design. (A similar model is described by Brezet, Cramer and Stevels as "The BCS-ladder") It shall be explained at this point because it offers an explanation for interrelations between the terms and approaches named above.

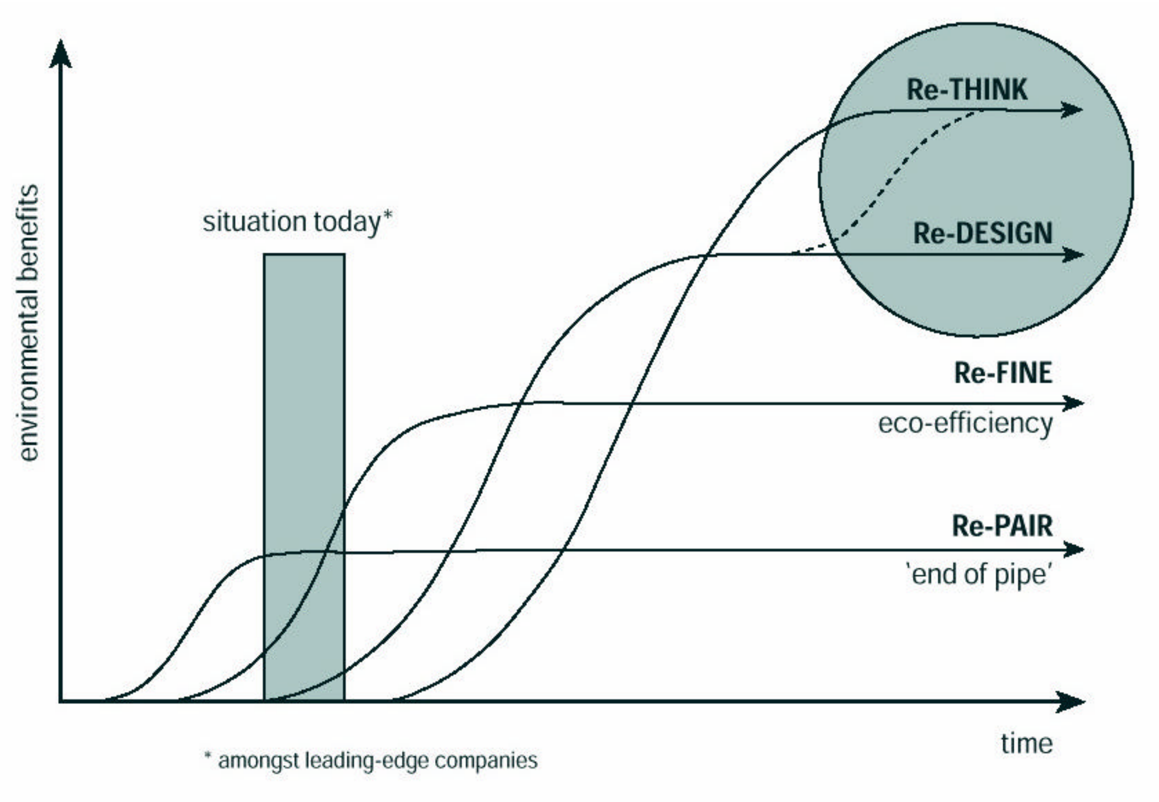


Figure 5.1: The 'Four steps' model [Charter/Chick 97]

The model shows four qualitative curves of "environmental benefit" over "time" leading to four levels of environmental benefit, namely Re-pair, Re-fine, Re-design and Re-think (examples added by the author):

- **Re-pair** designs are 'end-of-pipe' solutions. An example are filters that are added on existing technology
- **Re-fine** designs involve the 'designing out' of environmental implications at the source, however only resulting in incremental improvements. An example may be a TV set with an improved colour ray tube (CRT) and electronic circuits resulting in slightly lower electricity consumption.

According to Charter and Chick, these two levels are today reached by leading-edge companies using eco design. There are, however, two more beneficial levels, which they consider to characterise Sustainable :Product Design (encircled in fig 5.1)

- **Re-design**, which results in more than incremental environmental improvements in the products. A TV set with an LC-Display may be an example. Such LCD panels have a substantially lower electricity consumption than comparable CRTs (about 10 … 20 % of that of a CRT, see producer data sheets)

- **Re-think** is the highest level in the “Four steps” model. In order to reach this level the development of a more systemic infrastructure to enable the cyclical flow of resources and energy within product systems. A practical example for such design might be a standardised LCD panel to be used for several services (TV, Internet, etc.) and which would be fully recyclable.

Charter and Chick themselves name the “Baygen Freeplay radio” (shown on the left) as an example of a more sustainable product, as this radio uses a wind-up mechanism and a small generator to produce the electricity for the radio. The radio is, therefore, independent of mains electricity, batteries or solar cells.

Even further goes the concept of “services instead of products” and “De-materialisation”, e.g. [Brezet.00] Here, physical products are to be replaced by services, thus reducing energy and material consumption. An example are answering machines that can be replaced by a mailbox service provided by telecommunications companies.

Categorisation

In an attempt to categorise the terms with respect to their extent, one can - inspired by [Simon et al. 98] - consider Sustainable Design as the overall activity which comprises LCD, Ecodesign and DFE at the first lower level and specific DFx activities, e.g. Design for Recycling, at the second lower level.

Sustainable Design
Life Cycle Design, Ecodesign, Design for Environment
Design for Recycling, Design for Disassembly, etc.

As the general expression for the terms named in this section, *Environmental Design* - and synonymously sometimes *Life Cycle Design (LCD)* in its meaning mentioned above - will be used in this thesis.

5.4 The environmental design process and its two general activities

The environmental design process consists of the same main steps as the product development & design process as such (see Pahl & Beitz’s model in Chapter 3): The main steps are “Market need”, “Concept development”, Embodiment design” and Detailed design” followed by the production of the product. In order to illustrate the integration of environmental decision-making into this process, several model have been developed, e.g. [Schott et al. 97a, b, Olesen et al. 96, Wegst/Ashby 98]. Unique is McAloone’s model as it describes the design integration process and not the design process as such [McAloone 98].

Most of these models integrate LCA as a tool for the *verification* of the environmental improvements realised in a newly developed product.

There are, however, two main activities of the environmental design process:

- Idea generation - Generation of ideas for new solutions and
- Solution assessment - Assessment of the newly developed solution (and its relation to the previous old solution)

As will be shown in sections 5.6 and 5.7 of this chapter, the tools and methods existing so far, often support only one of these two activities. Guidelines, for instance, are good for idea generation but often useless for solution assessment. LCA methods, on the other hand, facilitate the assessment of solution but do not assist directly in generating ideas. The number of tools existing for ‘Idea generation’ is by far smaller than the number of ‘Solution assessment’ tools (Here, it shall be pointed out again that full, streamlined and matrix-based tools for environmental evaluation all support ‘Solution assessment’, see chapter 3). A reason for this circumstance is assumed to be the practical difficulty in generating quantitative suggestions for a new, potentially improved product on the basis of few known and a large number of unknown parameters.

It is, therefore, believed by the author that methods for quick quantitative ‘solution assessment’ are the best way to support designers in their work.

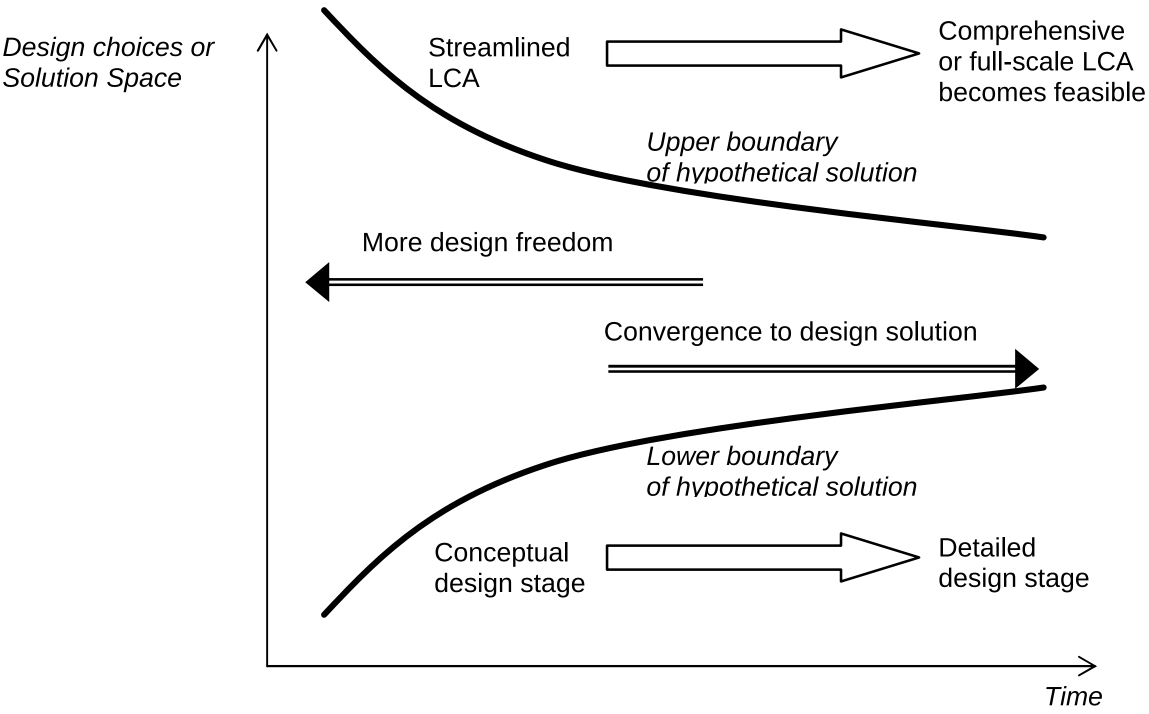


Figure 5.2 The Design solution space as a function of time, adapted from [Keoleian 94]

5.5 Rough information in early design

A key element in early design is that data and information may well only be "rough" in order to be useful. They only have to be correct in the order of magnitude. Examples for such rough information are:

- *"The usual lifetime of a TV set is around 10 years"*
- *"A typical hair dryer has an electrical effect of 1000 W"*
- *"The world-wide annual production volume of mobile phones is in the order of a couple of million units"*
- *"A car weighs about one tonne (1000 kg), of which ca. 700 kg are metals (mostly steel), 200 kg polymers and the rest other materials"*

Approximate figures like this are often sufficient as an indication of the situation in a specific case. Overall decisions, say upon a realistic target fuel consumption of the car, can already be based on such figures. In early design stages more detailed information is, thus, usually not required. The type of decision made in early design is rough and so is the type of required data.

It can, therefore, be assumed that, concerning information on environmental consequences related to a product concept at hand, this low level of detail is sufficient as well. If – based on rough information – an environmental evaluation shows that two concepts already at a very early design stage turn out to differ substantially in their environmental performance, they are very likely to do so in the detailed form as well. Exceptions are always possible, but generally, this can be assumed to be the case.

In Chapter 3 on Environmental Assessment, it was shown that there is one other major factor influencing the result of an environmental evaluation besides the more physical data: the model of the product system. Many parts of this model of the product system have to be assumed, per se. These assumptions, however, *can* only be approximate. The important thing in product system modelling is, however, that certain key factors are taken into account such as ‘lifetime’ and ‘expected production volume’ (see Chapter 3).

For decision-making in early design stages this means, that certain key factors have to be considered in the product system model, but that the quantification of these factors can be approximate.

With this understanding, existing tools and methods for environmental design shall be examined in the next section.

5.6 Three types of approaches

Full LCAs are time-intensive, as especially data collection but also product system modelling and scenario calculation – despite computer-support - require considerable efforts. Durations between a couple of months to one or two years are not unlikely for full LCAs. Wenzel illustrates time requirements in the way shown in **figure 3.5** (page 36) [Wenzel 98]. The high amount of time required represents the main drawback for application of LCA in companies, especially in short-cycled product development. Rough decision-making at the conceptual level is very difficult if not impossible with formal LCA methods as the level of detailed knowledge about the product required for the LCA does not exist at the conceptual level. Therefore, abridged methods have been developed. They can be divided into indicator-based and matrix-based methods. A third category comprises guideline-based methods. These don’t facilitate LCAs (as guidelines per se cannot be used to assess a product but only to generate solutions) but they support environmental assessment and are widely used in practice.

5.6.1 Indicator-based approaches

In indicator-based methods, the environmental impact is “condensed” to a single figure expressed per quantity, i.e. a ratio. For a material, for instance, an indicator could be the ratio could be “environmental damage / kilogram” or “environmental damage/ volume”.

The application of indicator-based methods is straightforward: The quantities needed for the product system are determined and subsequently multiplied with the respective indicator. The resulting figures (i.e. mathematical products) are summed-up over each life cycle stage and over the whole product system resulting in a single overall score. A product can be analysed e.g. by comparing the results for the life cycle stages with each other. Different product solutions can be easily compared by means of the single overall scores.

The main drawback of indicator-based methods is the fact that the indicators are pre-calculated by the method provider. Whenever indicators for the product system at hand, e.g. a certain material, don’t exist their application is difficult or even impossible (depending on how many indicators are missing in the product system and on the experience of the user). Another generic problem is lack of transparency, as it can not be directly seen why a certain indicator has a high or low value.

Established methods that use indicators are “EPS” from Sweden (Environmental Priorities Strategy), e.g. [Ryding et al. 95], the Dutch “Eco-indicator 95”, e.g. [Goedkoop 95a] and the German “MIPS” (Material Intensity Per Service unit), e.g. [Schmidt-Bleek 98]. They differ in the kind of environmental damage considered and, related to that circumstance, the set of indicators existing. MIPS, for instance, is the only method of the ones mentioned, which considers *water consumption* as a specific impact category (actually also of all other formal or abridged methods known to the author). Related indicators are thus not given in the other methods.

5.6.2 Matrix-based approaches

In matrix-based approaches, environmental exchanges of the product system are reflected in a matrix of life cycle stages over environmental impact sources or, depending on the method, sources and sinks. For their application, the matrix is filled out with quantitative or qualitative data (e.g. “15 kg Aluminium” or “high amount”). The result is a diversified and transparent picture of the environmental performance of the product. For a single product the most important life cycle stage can be determined, if a trade-off between the importance of the different environmental impacts is done. This usually involves expert knowledge. The comparison of different product solutions can be difficult, e.g. if the solutions compared have high potential impacts in different categories.

In the context of full LCAs, matrix methods can be used as an initial tool for environmental specialists to determine focal areas for a subsequent full LCA. (This is done in the EDIP method.)

Established matrix-based methods are:

- the Dutch MET-matrix (focus: Materials, Energy, Toxicity), e.g. [Brezet/van Hemel 97],
- the American Environmentally Responsible Product Assessment Matrix (focus: Materials, Energy and Gaseous, liquid and solid residues), e.g. [Graedel/Allenby 95] and
- the MECO matrix (Materials, Energy, Chemicals, Other), e.g. [Wenzel et al. 97], p.135, see also Chapter 3.

5.6.3 Guideline-based approaches

Guidelines are textual descriptions of design principles. They usually contain no quantitative information.

One can distinguish *prescriptive* and *prohibitive* guidelines: The former describing environmentally preferable design principles, e.g. “Choose light and stiff materials”, the latter describing things to be avoided, e.g. “Avoid composite materials as they are difficult to recycle”. Setting so-called “red-flags” can be done in combination with prohibitive guidelines. Here, environmentally problematic parts of the product or life cycle stages are marked with a red flag. The solution with least red flags is then recommended.

The application of guidelines is straightforward, but only valid within a restricted field of products or technologies (compare Product family approach in Chapter 3). Guidelines have the advantage that they can lead the designer in a certain design direction and thus give active help for generating solutions. However, in a set of guidelines contradictions are likely to occur or they are so obvious (e.g. “save material”) that their mentioning is obsolete, compare [Hauschild et al. 99]. In the example above, the preferable light and stiff material may well be a composite material. If there doesn’t exist a weighting of the different guidelines, and this is the typical case, decision-making can be difficult. Both a product analysis and comparison of solutions are affected by this difficulty. Thus, guidelines cannot be used here.

5.7 Tools & Methods for environmental product development

Concerning tools and methods that support environmental decision-making in product development and design, two general classes shall be distinguished:

- Tools supporting organisational decisions and
- Tools supporting operational decisions

The former class comprises tools, which support finding and defining strategies for a company.

They address the product development process as such and suggest at which points in the product development process environmental issues become relevant and how to tackle them.

The latter class comprises tools, which are meant to be used for decisions on the product as such. Within this class, there are both generally applicable tools and methods, i.e. methods that can be used in all stages of product design, and more specific tools; among them, some especially for environmental materials and process selection.

Both types interrelate and have overlaps. The EDIP method [Wenzel et al. 97], for instance, represents a toolbox with several tools in both classes. LCA methods in general, however, be they of the full formal type or more simplified, matrix- or indicator-based, usually address the general operational level (compare Chapter 3).

Therefore, two methods addressing product development as such shall be described subsequently.

In a later section, tools developed especially for environmentally conscious selection of materials and processes will be described and compared.

Furthermore, individual companies often give priority to certain environmental parameters. On the basis of an LCA result, however, the performance of a product solution with respect to some of these environmental parameters may not be clear.

The Dutch consumer electronics company Philips, for instance, prioritises the following five environmental parameters in their environmental product development, which they call “Green Focal Areas” [Philips 98], p. 9 (In the sequence below, it might be referred to as WHERP principle):

1. Weight, i.e. weight of the product and of its components and number of materials
2. Hazardous substances, i.e. number of restricted substances
3. Energy consumption, i.e. energy used by the product in kilowatt-hours
4. Recycling and disposal, i.e. material recycling efficiency (in the end-of-life stage) as a percentage of the total product weight
5. Packaging, i.e. weight of packaging materials as a percentage of the total product weight

In order to facilitate the consideration of such parameters, tools like the “Ecodesign strategy wheel” have been developed, **fig. 5.3**.

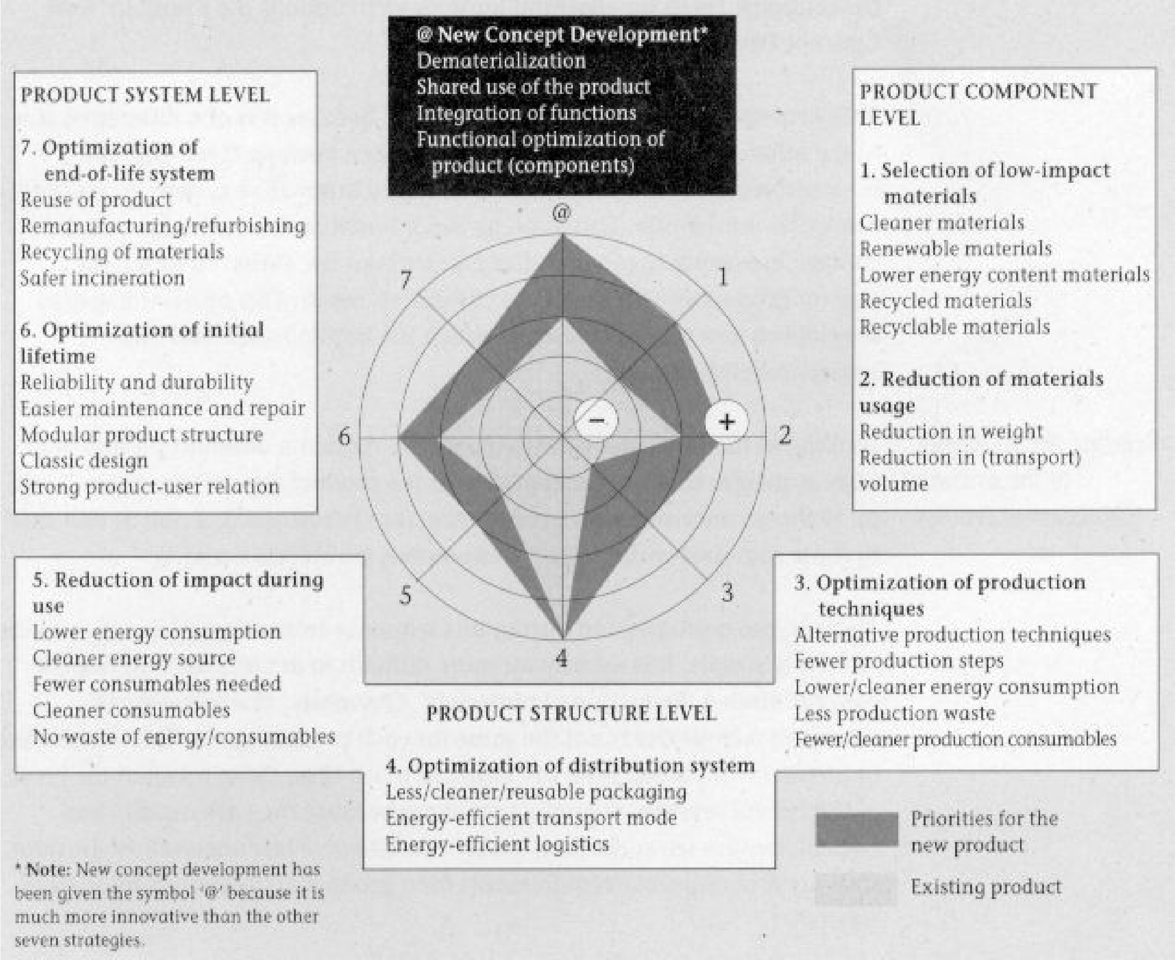


Figure 5.3 The Ecodesign strategy wheel, [Brezet/van Hemel 97], p. 81

The Ecodesign strategy wheel visualises the performance of a product solution with respect to eight general strategies that can be followed in environmental design. The strategies – indicated along the circumference of the wheel – mirror product life cycle stages and are grouped according to the level where they have an effect:

- Product component level
- Product structure level
- Product system level and
- New concept development

The strategies on these levels include among others (compare **figure 5.3)**:
- “Selection of low-impact materials” (Strategy 1),
- “Reduction of materials usage” (Strategy 2),
- “Optimisation of production techniques” (Strategy 3) and
- “Reduction of impact during use” (Strategy 5)

Brezet/van Hemel mention “New concept development” as the most challenging strategy (indicated by an ‘@’ in fig 5). With ‘concept’ they mean product utilisation concepts, e.g. the shared use of products, rather than product concepts, which describe the product as such in terms of its working principle and candidate materials (see section 4.2.8).

The basic advantage of a tool such as the Ecodesign strategy wheel is that the performance of a product solution is visualised by the size of an area. The larger the area covered by the solution, the better it is. This may help in trade-off situations between different strategies.

The quantification of the performance in the radial direction, however, is recommended to be done by means of LCA methods. (This, in turn, implies the utilisation of indicator-based LCA methods, as they produce results with a single score for each life cycle stage.)

The approach allows a multi-dimensional comparison of two or more product solutions. It has, however, some drawbacks, one of them being the fact that it does not mirror the crucial point, that changes on the three different main dimensions may have highly different environmental importance.

Holloway

Holloway [Holloway 97] developed a more analytical tool, the “Environmental Design Strategy Guidance Matrix (EDSG Matrix)”. This matrix contains sets of guidelines for the life cycle stages of classes of products. He suggests to classify products in a binary way after their:

1. Energy consumption: Energy consuming or not
2. Resource consumption: Resource consuming or not
3. Material requirement: Multi-material or single material
4. Configuration: Multi-part or single part and their
5. Disposal route: Returnable or non-returnable.

In each of these classes, a separation is suggested into long or short life length.

A guideline for the end-of-life stage of a multi-material product with a short life cycle, for instance, says [Holloway 97], p. 150:

> *“Multi-material products will have complex disposal effects. Many different strategies should be considered, such as material compatibility, fixing and bonding, general disassembly rules etc.”*

Based on such specific guidelines, strategies for improvements can be developed. These, in turn, can be verified in a strategy checklist.

Olesen et al.

Another more complex product development-related method is suggested by Olesen et al. [96]. Here, a milestone management plan is suggested, where environmental questions are elaborated over all product development stages. The elaboration is done on the levels (see [Olesen et al. 96], fig. 27, pp. 51 and 58/59):

- Focusing
- Goal setting
- Synthesis of product

- Definition of life cycle and
- Verification

This method also includes a set of guidelines for environmental materials selection. It will be discussed in the next section together with other tools and methods specifically developed for this task.

Other tools for use in product development are suggested e.g. by Bhamra et al. [97], Schott et al. [97] and Dannheim [99].

5.8 Tools & Methods for environmental materials & process selection

The main focus in this research is the support of designers in environmentally conscious selection of engineering materials and manufacturing processes. Existing methods developed for this task are, therefore, discussed in this section.

Materials and manufacturing have been in the focus of environmental concern for a long time mainly due to aspects of resource consumption and pollution. Many contributions to this field can, therefore, be found in literature. Zhang et al. give an overview over methods and tools in Environmentally Conscious Design and Manufacture ECDM [Zhang et al. 97]. They mention more than a hundred unique references. About a fifth of them relate to materials and process selection as such. Others concern DFE, Recycling, waste or disassembly issues.

As explained in sections 5.4 and 5.5, it is believed by the author that the support of designers can be achieved best with methods for quick quantitative ‘solution assessment’, i.e. quick and quantitative environmental assessment methods. In Chapter 3, two types of methods for quantitative environmental assessment have been distinguished:

- Indicator-based methods
- Matrix-based methods and

The following sections discuss methods of each type. The methods are either specifically developed for environmental m/p-selection or are general environmental assessment or design methods, which incorporate a special section on materials issues. The methods have been selected because of their broad acceptance in academia and reported use in industry. IdeMat [98], computer tool for environmental materials selection, is not described in this section as it will be explained in detail in the next chapter.

5.8.1 Matrix-based tools & methods

Graedel & Allenby’s “Environmentally responsible product-assessment matrix” (ERPA-matrix) is an example for a matrix-based assessment method, which incorporates detailed materials-related issues, see e.g. [Graedel/Allenby 96], p. 106 ff. (The authors suggest a similar matrix for process assessment.)

It is a 5 x 5 matrix with the five life cycle stages as one dimension and “environmental concerns” as the other, see **tab. 5.1**.

	Environmental concerns				
Life stage	Materials Choice	Energy use	Solid residues	Liquid residues	Gaseous residues
Pre-manufacture	1,1	1,2	1,3	1,4	1,5
Product manufacture	2,1	2,2	…	…	…
Product delivery	3,1	…			
Product use	4,1				
Refurbishment, recycling, disposal	5,1				

Table 5.1 Environmentally responsible product-assessment matrix. Numbers of matrix elements is indicated. Those matrix elements regarding materials selection are shaded, adapted from [Graedel/Allenby 96], p. 108

For each matrix element, the authors offer a set of guidelines. Those for element 2,1 (Materials Choice, Product Manufacture), for instance are [Graedel/Allenby 96], p. 152:

- “Is the product designed to avoid or minimise incorporating materials that are in restricted supply?
- Is the use of toxic materials avoided or minimised?
- Is the use of radioactive materials avoided or minimised?”

The designer uses such guiding questions to assign integer values between 0 (for a high expected impact) and 4 (for a low expected impact, i.e. a good performance) to each matrix element. In order to assess the whole product solution at hand, all integer values are summed-up to an overall rating. (They can also be plotted as on a target plot diagram).

The assignment of estimated, non-absolute values is purposely suggested by the authors in order to make the method utilitarian.

Main characteristics of this method are:

- The tool leads to quantitative results, which are non-absolute and estimated
- External data are not required, except for the sets of guidelines

Other characteristics are listed in section 5.9

The Product Environmental Property Scheme

Based on Andreasen's Domain Theory [Andreasen 80], described in Chapter 4, an integrative description of a product can be done by means of a so-called *product-property scheme*. This scheme visualises two things: On the one hand the relations between elements of the product (both within and across the domains) and, on the other hand, the relations between the parts of the product and their technical properties.

Relations of the latter kind, for example, make it possible to determine those parts that have the strongest relation to certain properties and thus have the strongest influence on the performance of the product as a whole.

With respect to environmental analyses and assessments of products, especially those technical properties relating to environmental performance are of particular interest. An excerpt of a product-property scheme used to investigate relations between parts of an electric shaver and environment-related technical properties is given on the next page. This modified scheme is called "Product-*Environmental* Property Scheme, (PEP scheme)".

The PEP scheme was developed by the author during a Ph.D. course on Design Methodology lead by Prof. Andreasen, see [Bey 97]. It shows relations between properties and functions and is, thus, an analytical tool. Its results can be used as a basis for the generation of ideas on the detailed design level.

Clear drawbacks of the PEP scheme are that it does not give quantitative results and that environmental relations are not structured, e.g. according to M, E, C and O. Especially qualitative result are, however, necessary for making comparisons of options during the design process. Therefore, the idea of making a PEP scheme was not followed further on.

An established Matrix-based method that could be used for materials selection is MECO, where the LCA work is structured after their source, i.e. Materials, Energy, Chemicals and Others, see Chapter 3.

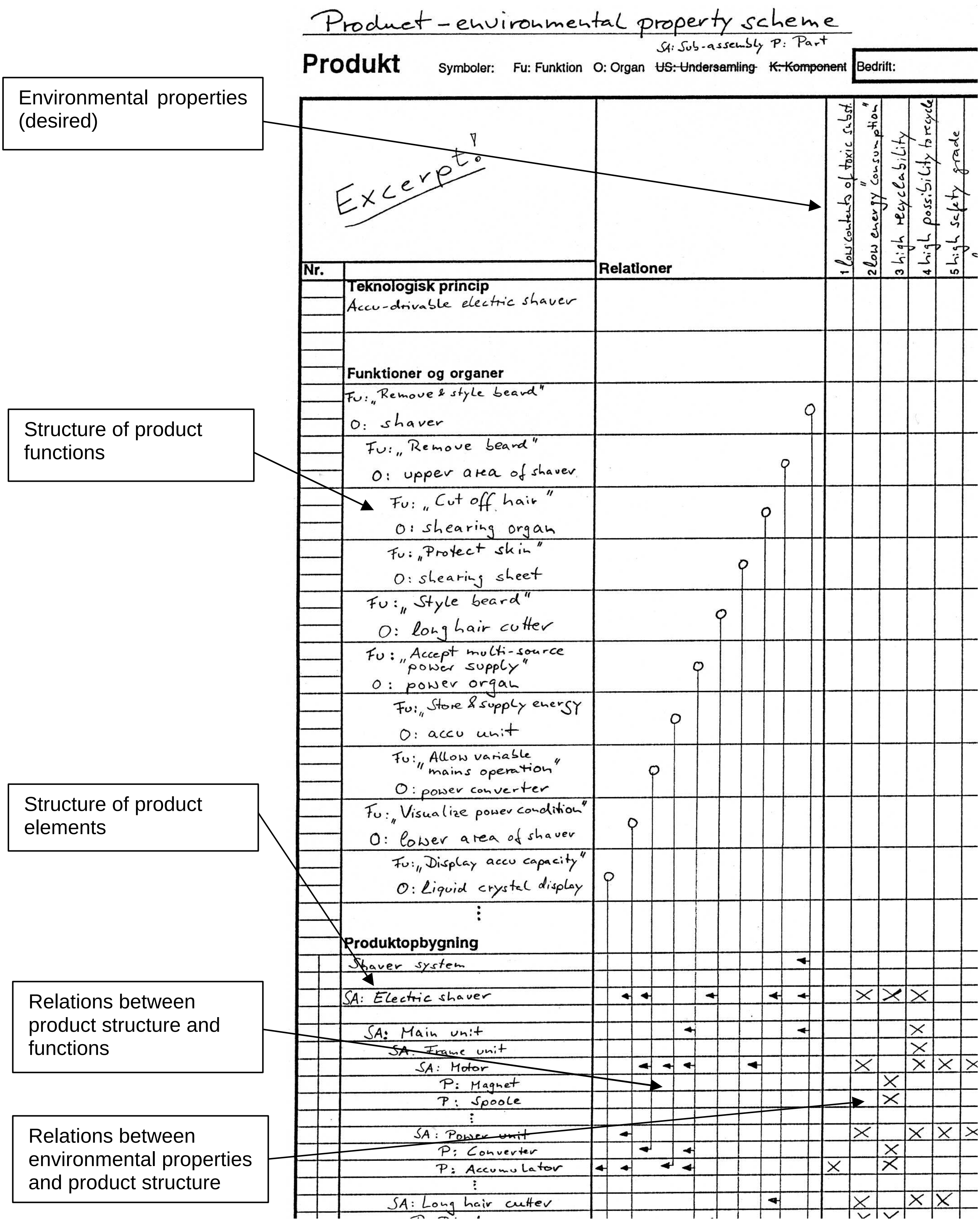


Figure 5.4 Excerpt of a 'product-environmental property scheme' for an accu-drivable electric shaver [Bey 97] For instance, the desired environmental property "low contents of toxic substances" is determined to be related to the NiCd-based accumulator, which in turn is related to four functions, among them "accept multi-source power supply"

5.8.2 Indicator-based tools & methods

Rombouts/Hennessey explore making materials selection by means of pre-defined groups of materials in which they intend to use one common indicator value. They also investigate, whether electricity transformation can be generalised, in order to avoid having to use country specific electricity depending on in which country the product is used, [Rombouts/Hennessey 99].

They use materials Eco-indicators [Goedkoop 95 a, b], EPS values (see [Ryding et al. 95]) and Gross Energy Requirement (GER) values as metric for comparison - all extracted from the database tool IdeMat [IdeMat 98].

Concerning materials, they conclude that a grouping does not lead to high deviations from the detailed analysis (with material-specific indicators), for electricity, however, it does. All in all, they conclude that the GER is not applicable for Ecodesign, because it is not sensitive against country-specific fuel mixes.

However, they disregard the circumstance that the high deviation concerning electricity is based on the inclusion of Norwegian electricity (, which is almost completely based on water power and thus very low-polluting). As discussed in Chapter 3, the special case Norway should have been disregarded. The deviation would then have been extremely lower, making GER (or primary energy requirements) a useful option.

Other indicator-based approaches for materials selection use money as a metric for comparison, see [Chen et al. 94, Chen 95]. Environmental cost-based approaches, however, suffer from the problem that Environment cannot be objectively expressed as cost, as market mechanisms always play a decisive role here. Stuart/Sommerville [98] give an overview over qualitative (guidelines) and quantitative materials selection tools.

5.8.3 Others

Holloway [98] investigates the utilisation of Ashby’s Materials Selection Charts for environmentally conscious materials selection. He expands the view on environmental parameters relevant for materials from energy (i.e. Energy content vs. Young’s modulus, **fig 5.5**) over to water respectively airborne emissions and suggests using charts such as Young’s modulus vs. NO_x emissions or Young’s modulus vs. Air pollution index. These charts allow an environmentally more specific selection of materials on the basis of extraction and production data.

However, they lack a crucial element of environmental evaluation: the dimension of time and thus impacts resulting from other life cycle stages.

As stated earlier in (Chapter 2), a low environmental impact related to the extraction and production of a material does not mean that the material seen in the product life cycle perspective will perform better than a material with an initially higher pollution.

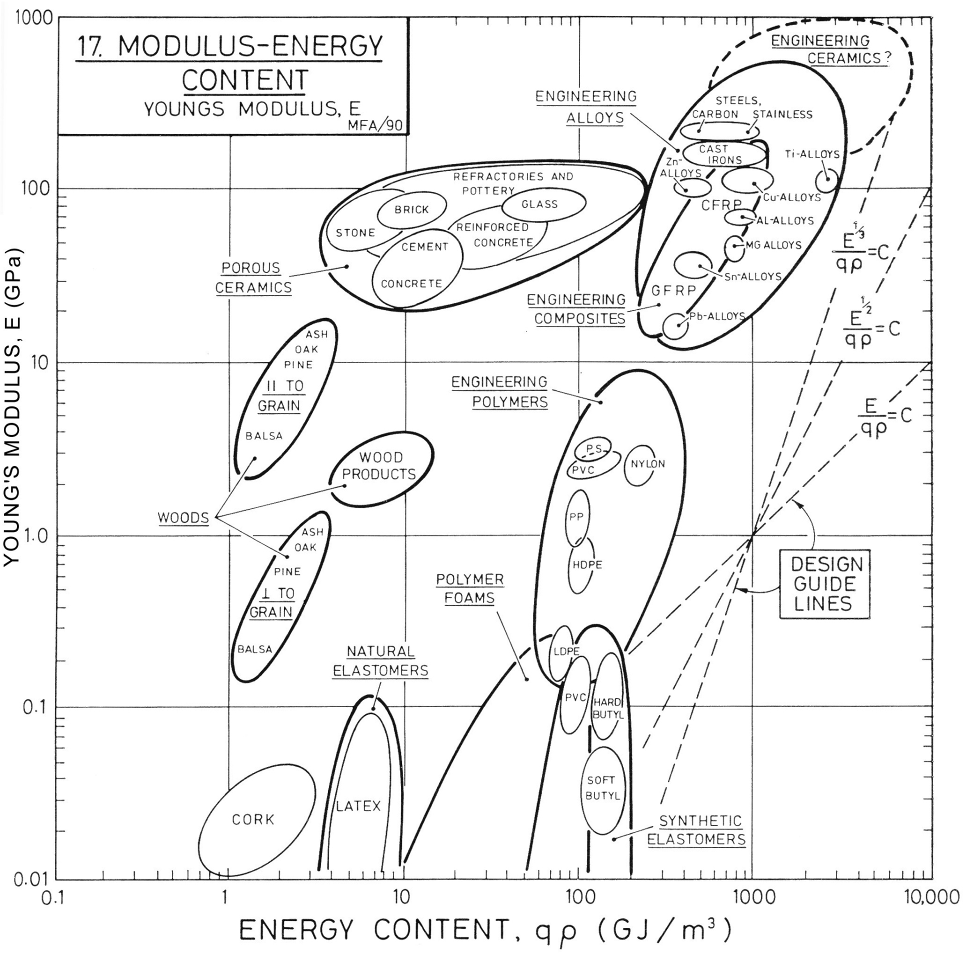


Figure 5.5 A materials selection chart showing Young's modulus vs. Energy content, [Ashby 96]

Ashby's method for materials selection was discussed in section 4.3.

De Winter [98] investigates environmental aspects of sheet metal forming. His environmental metric is 'energy consumption'.

EuroMat is a joint German research project for the environmental and economic selection of composite materials, [Fleischer et al. 97, EuroMat 98]. Recyclability and working environment are considered as well. EuroMat represents a top-down approach (similar to Ashby's) where the selection process starts off with all materials and material combinations and where the optimal material/combination is determined under a life cycle perspective.

This approach is quite comprehensive and requires expert teams for its application.

5.9 Comparison of tools and requirements in Environmental Design

A recapitulation of the requirements and constraints in environmental design elaborated so far in this thesis includes:

1. It is commonly recognised that any environmental assessment and decision-making has to be done with a *product-related life cycle perspective* (Chapter 3)
2. In the same way, it is recognised that any comparison of solutions has to base on a *Functional Unit* description (Chapter 3). The decisions in materials and process selection are *always* based on comparisons.
3. Decisions made in the *early design stages* have the highest influence (Chapter 4). This applies also to environmental design decisions.
4. Decision-making in environmental design requires both *qualitative and quantitative* information. Results have to be quantitative in order to facilitate direct comparisons of solutions.
5. In order to be comparable with LCA results (, which is the scientifically recognised way of conducting an environmental assessment), quantitative data used in environmental assessments have to be *absolute*. The assignment of an estimated integer value leads to quantitative but non-absolute results.
6. In the early design stages, designers (especially industrial designers), require *rough, "quick-and-easy" to use* methods for the assessment of newly developed product solutions (this chapter). This includes *accessibility of absolute data*, see e.g. [Bakker 95] and [McAloone 98].
7. If designers are to make environmental assessments of solutions by themselves, *indicator-based methods and matrix-based methods* seem to be most appropriate.
8. As these assessments should be full-quantitative – in order to facilitate quantitative comparisons - , indicator-based methods seem to be most appropriate for designers.

The tools and methods for environmental design, including materials and process selection, are compared against the above mentioned requirements in **table 5.2** together with MECO.

Approach:	**Indicator-based**	**Matrix-based**		**Guidelines**	**Others:**
Method: **Criterion/Requirement:**	[IdeMat 98] & Eco-indicator 95 method	[Greadel/ Allenby 97]	MECO [Wenzel et al. 97]	[Olesen et al. 96]	[Holloway 98]
Product life cycle-based approach	✓	✓	✓	✗	✗
Functional unit-based	✓	✗	✓	✗	✗
Rough calculations	✗	✓	✓	-	✗
Quick application	(✓)	✓	✓	✓	✓
Environmental data provided as indicators	✓	✗	✗	✗	✓
Based on absolute data	✓	✗	✓/✗	-	✓
Quantitative results	✓	✓	✓/✗	✗	✓

Table 5.2 Comparison of requirements for environmental materials selection methods with features of four methods designed for the task and with MECO

5.10 Conclusion

Many tools and methods for classic materials and process selection incorporate also environmental aspects. The idea to clearly distinguish tools for environmental materials selection from other tools turned out difficult.

However, there are also tools that aim specifically at supporting environmentally conscious materials selection but do not fulfil general requirements, such as the basis in the life cycle approach.

Environmental impacts of materials have to be seen in a lifecycle perspective of the product as a whole. This is not considered in many existing methods for environmental design.

The environmental materials selection process requires quantitative environmental data. Guidelines alone are not sufficient.

None of the existing tools fulfils all requirements. Some crucial criteria, such as the basis of comparisons on a Functional Unit, are only fulfilled by two of the tools. This justifies the development of a new tool, which takes *all* of the requirements into account.

6 The Oil Point Method for Environmental Selection of Materials and Processes

The previous chapters of this thesis explained the context for the development of a method for environmental materials and process selection. This chapter describes the suggested solution, the ‘Oil Point Method’.

First, however, a short recapitulation: The context for the development of the OPM was explained by answering four main groups of questions. These were:

1. “What is the overall problem?” and “How could a solution to this problem look like?” (Chapter 2)
2. “How can one ‘measure’ (i.e. quantify) the extent of this problem, i.e. how can one measure impacts caused by products?” (Chapter 3)
3. “What can designers do about the problem when selecting materials and processes?” and “Which requirements do they have upon supportive tools?” (Chapter 4)
4. “Which tools do they have at their disposal?” and “Are these tools sufficient?” (Chapter 5)

Answering the first group of questions was accomplished by describing today’s environmental situation and by explaining the concept of Sustainability as a solution. It was argued that, if a Sustainable Development is to be achieved, negative implications of human activity have to be reduced substantially. Finally, the special role of products and of environmental product development in this context was pointed out (Chapter 2).

The second group of questions was answered by describing principles and the state-of-the-art in making environmental life cycle assessments of products and systems (LCAs) (chapter 3). It was argued that environmental assessments are always based on a set of values, which was termed the “underlying environmental mind-set”. From the point of view of LCA, a minimum set of requirements upon a simplified evaluation method was extracted.

These LCA-related requirements were:

- The method has to be **based on the life cycle approach**, thus all stages in the life cycle of the product have to be considered and
- Comparisons of alternatives have to be **based on a Functional Unit**, which describes temporal, geographical, qualitative and quantitative aspects of the product (or service).

Regarding the third group of questions, i.e. designers possibilities and requirements, the importance of the role which designers play in the development of environmentally-conscious product and service concepts was pointed out. Requirements upon methods for environmental evaluation in early stages of design were defined as well (chapter 4). The two dominant design-related requirements were:

- In order to be applicable in the very early stages of product development, the method should be relatively **quick in application** e.g. by avoiding intensive data retrieval and
- The method should use **quantitative data** (as opposed to qualitative data, checklists or general guidelines - i.e. not product family-specific guidelines) in order to facilitate unambiguous comparisons of alternatives

For clarifying the fourth group of questions, existing tools and methods for environmental product design were critically reviewed in chapter 5 with the result that none of the existing methods and especially not the ones dedicated to environmental materials and process selection, fulfilled both design-related as well as LCA-related requirements.

This chapter

This chapter introduces a method, which encompasses all those requirements. The method proposed is the ‘Oil Point Method’, abbreviated OPM. The OPM is developed to support designers in the process of selecting engineering materials and manufacturing processes with respect to environmental aspects. In this way, the method encourages environmentally conscious product development and design.

The following sections explain the OPM - first briefly and then in more detail by means of an exemplary case study. Rules for its application are described. The important field of data acquisition and data quality is treated as well, especially the way it affects Oil Point evaluations. At the end of this chapter, characteristics of the OPM are discussed, especially its basis in energy contemplations.

6.1 Essentials of the OPM

Aim:
Rough evaluation of options

The Oil Point Method is a method for rough environmental evaluations. The method indicates an overall environmental performance for different technological options a designer is examining as potential solutions.

Measure:
Indicators for environmental impact

Environmental impacts related to producing or disposing of a material or process are expressed by ‘Oil Point indicators’. An Oil Point indicator is a ratio of environmental impact (expressed as primary energy) per amount of material, per transport distance, per consumed electricity, etc.

Focus:
Energy-related environmental impacts

The “environmental mind-set” behind the OPM is limited to “natural environment” and focuses on impacts caused by fuel combustion processes. The method thus focuses indirectly on impact categories such as Global Warming, Photochemical ozone formation and Acidification, among others. Impacts from toxic substances are not considered.

As not energy requirements as such are in focus (and not balanced, either), the OPM is no Energy Analysis over the life cycle.

Target group:
Designers

The OPM is a tool for “designers”. This term is understood as comprising product developers, engineering designers and industrial designers. Generally, target group are individuals, who do not have deeper knowledge in environmental assessment.

Character:
Rough but holistic

The overall environmental performance of the product or service examined is deliberately meant to be shown only *roughly*, i.e. rather as an indication than as a detailed portrayal. The designation *“environmental evaluations in orders of magnitude”* may, thus, be appropriate. The intention of this approach is to give designers a tool, which appreciates their specific demands by, among other things, indicating, which option represents “the right path to a detailed solution” in a holistic perspective.

Intention:
Increased applicability

Compared with other methods for environmental evaluation, the intention with the OPM is to improve applicability. It is assumed that - provided a valid overall scientific basis - the “routine use” of a method is a crucial element in increasing the effectiveness of methods for environmental product development (compare Chapter 5).

Overall structure:
Based on LCA

On the overall level, the structure of the method is based on that of a formal Life Cycle Assessment. The individual phases, however, are shortened or modified. (Inventory Analysis is limited to the input side and Impact Assessment is not performed as such but implicitly included, as energy-related impact categories are among the most discussed impact categories.) Instead of an “Impact Assessment”, primary energy consumptions are accounted as an indicator for related environmental impact.

Procedure:
Three steps

The method has three steps:
1. “Focus”, comparable to Goal & Scope Definition in LCA,
2. “Evaluate”, the modelling and accounting and
3. “Interpret”, where the result is seen in a larger context.

Missing OP indicators can be estimated

Indicator-based methods, per se, suffer from the problem that indicators are often missing for a specific material or process. What is more, the indicators are usually compound indicators, which means that they cannot be estimated. In the OPM, this problem is encountered by using "primary energy requirements" as a non-compound indicator allowing the estimation of missing Oil Point indicators and by supplying aids for this task.

Overall intent

The overall intent with the simplifications represented by the OPM is to make sure that all phases of an LCA are taken into account while holding the effort at a level suitable for conceptual material and process selection by designers.

6.2 What are "Oil Points"? - Definition

Oil Points are a unit for primary energy, i.e. for the energy content of energy carriers that have not yet been subjected to any conversion. One Oil Point (OP) equals 45 MJ, which is the energy content of 1 kg of crude oil, see [Boustead 97]. Oil Points are defined for

- materials, (separately for fuel share and feedstock share, see below),
- fuels, as they are carriers of primary energy and
- processes, as they 'consume' primary energy, either directly or indirectly. The term 'processes' covers
  - manufacturing processes,
  - transport processes,
  - use processes and
  - end-of-life processes

The result of an Oil Point evaluation is a simplified and approximate expression of the amount of primary energy, which is required for or released in the processes during a whole product life cycle.

Fuel energy and Feedstock energy

With respect to fuel bearing materials, Oil Points also quantify the distribution between fuel energy and feedstock energy. *Fuel energy* is the share of the energy content, which is "lost" during processing, while *feedstock energy* is the share, which is included in the material as a fuel and may be recovered, e.g. by incineration, or is lost as waste. Only natural materials and plastics bear feedstock energy (see also section 3.7).

In order to derive Oil Points, energy consumptions are traced back to related consumptions of primary energy in the unit megajoule (MJ). These quantities of primary energy are divided by the energy content of 1 kilogram of crude oil, which is 45 MJ (compare [Boustead 97], who states 45 MJ/kg as the gross calorific value of crude oil).

The unit “Oil Equivalent” is used in energy statistics as a common denominator for energy values. The tonne of Oil Equivalent is here a “*conventional standardised unit defined on the basis of a tonne of oil with a net calorific value of 41 868 kilojoules/kg (i.e. 41.868 MJ/kg),* [EUROSTAT 97], p. 5.

In this way, the primary energy requirements occurring during the life cycle of a product can be expressed as dimensionless “Oil Points”. Any Oil Point result for a given product system can thus be understood as “kilograms of crude oil” that trigger environmental impact in that specific product system. It is thus obvious that a low Oil Point figure indicates a low environmental impact.

The definition of an Oil Point is as follows:

“One Oil Point (OP) is the energy content of 1 kg of crude oil with the gross calorific value of 45 MJ/kg before it is extracted from the earth.”

1 Oil Point (OP) := 45 MJ = Inherent energy of 1 kg crude oil

Using this definition, the plastic material “High density polyethylene” (HDPE) equals 1.7 OP/kg from about 33 MJ/kg (or 0.7 OP/kg) processing energy (fuel energy) and about 46 MJ/kg (or 1 OP/kg) gross calorific value (feedstock energy) [APME 97]. The processing energy is needed for the chain of processes, which turn the raw material “crude oil” into HDPE resin.

Terms:

“Oil Point indicators”,

“Oil Point figures” and

“Oil Point sums”

In the example, 1.7 OP/kg are the “Oil Point indicator” for the material HDPE. For evaluations, such Oil Point indicators are multiplied by respective quantities occurring during the life cycle to give “Oil Point figures”. These figures are added-up to give “Oil Point sums” for each life cycle stage. The final result of the evaluation is an overall sum of all Oil Point sums, the “Oil Point result”. These terms are defined for explanation only. The actual calculations are relatively straightforward as the example below shows.

Oil Point indicator x quantity = Oil Point figure

“Materials Production of 2 kg HDPE granule”

$$1.7 OP / kg \times 2 kg = 3.4 OP \tag{6.1}$$

Wherever possible, Oil Point indicators are rounded to one decimal place in order to keep calculations simple and to reflect the uncertainty in general; an OP result with five decimals would suggest a too high degree of certainty (electricity and transport are exceptions). Amounts to be multiplied with the indicators are usually far below 100 which would make the possible deviation to be far below ± 10 OP. Therefore, the error introduced by this practice is considered to be negligible, as the character of the method is rough.

For fuel bearing materials, the indicator is further divided into fuel part and feedstock part, e.g. for HDPE: “1.7 OP/kg (0.7 OP/kg fuel plus 1.0 OP/kg feedstock)” or just “1.7 OP/kg (0.7/1.0)”.

The unit “Oil Points” [OP]

The reason for using the unit “Oil Points” rather than an SI-unit such as Joule [J] is, that it is supposed that designers will easily become familiar with such a less abstract unit.

This may also make the application of the method more likely. In the same way, the risk of errors is supposed to become smaller due to the intuitive understanding of the data values (compare [Bakker 95]).

The different unit may reduce errors also in another way: MJ vales given in a source may include efficiency factors or not. Oil Points, however, always include efficiency. Finally, the unit OP emphasises that the figures are not “regular” energy data but that there are some methodological choices behind it (such as the rounding). This would be hidden, if one would assign MJs.

A positive additional effect of normalising with the relatively large factor of 45 MJ is that Oil Point indicators and Oil Point results usually become figures greater than 1. Compared to a span between e.g. 0.0001 and 0.1, this span is easier to handle - especially by non-engineers – due to the reduced number of decimals.

Should an individual prefer the SI unit “MJ”, then any Oil Point value can be transformed to this unit by simply multiplying it with the factor 45.

On the next page a concrete brief example will explain the sort of calculations necessary for an Oil Point evaluation.

The calculation is made for a hypothetical passenger car.

6.3 An example: A passenger car

The table below shoes the calculations for an Oil Point evaluation of a hypothetical passenger car.

	Quantity	OP indicator		Result	
Materials					
Steel (90% recycled)	500 kg	0.4	OP/kg	200	OP
Cast iron (engine, gear box)	100 kg	0.6	OP/kg	60	OP
Copper (wires, electric motors)	40 kg	2.3	OP/kg	92	OP
Aluminium (different parts, 50% recycled)	70 kg	2.1	OP/kg	147	OP
ABS-plastics	60 kg	2.1	OP/kg	126	OP
HDPE-plastics	70 kg	1.8	OP/kg	126	OP
PC-plastics	70 kg	2.6	OP/kg	182	OP
PU foam (seats)	20 kg	2.2	OP/kg	44	OP
Rubber (tyres etc.)	50 kg	2	OP/kg	100	OP
Glass	20 kg	0.3	OP/kg	6	OP
Total net weight:	1000 kg		**Sub total:**	**1083**	**OP**
Manufacturing					
Sheet metal forming	500 kg	0.2	OP/kg	100	OP
Welding	100 m*	0.02	OP/m	2	OP
Injection moulding (plastics)	200 kg	0.4	OP/kg	80	OP
Rubber moulding	50 kg	3.4	OP/kg	170	OP
Lacquering, div. machining, forming, etc.				10	OP*
			Sub total:	**362**	**OP**
Transport					
Total net weight:	1 t				
Transport to factory, truck, 1000 km*	1000 t-km	0.01	OP/t-km	10	OP
Transport to customer, train, 500 km	500 t-km	0.005	OP/t-km	2.5	OP
Transport to recycling, train, 500 km	500 t-km	0.005	OP/t-km	2.5	OP
			Sub total:	**15**	**OP**
Use					
15 years x 15000km/year = 225000 km					
8 ltr. gasoline/km = 28125 l/225000 km	28125 ltr.	1.1	OP/ltr.	30938	OP
			Sub total:	**30938**	**OP**
End-of-Life					
Shredding	600 kg*	0.1	OP/kg*	60	OP
Aluminium recycling (90%* of original)	63 kg	0.3	OP/kg*	18.9	OP
Steel recycling (90% of original)	450 kg	0.2	OP/ kg*	90	OP
Copper recycling (70%* of original)	28 kg	0.2	OP/ kg*	5.6	OP
Plastics recycling (50%* of original thermoplastics)	100 kg	1.0	OP/kg (average)	100	OP
Plastics incineration (50%* of original total)	100 kg	1.0	OP/kg	100	OP
Landfilling of remaining materials	259 kg	0	OP/kg	0	OP
			Sub total:	**375**	**OP**
			Total:	**32772**	**OP**
			Total per year (rounded:	**2185**	**OP**

Table 6.1 An Oil Point evaluation of a hypothetical passenger car (* = estimate)

6.4 Oil Points and resource consumption

The OPM uses Oil Point indicators, which consist of a *fuel* energy share and, for some materials, of a *feedstock* energy share. Both shares have resource aspects:

- Fuel can be of fossil origin, which means that it is a finite, non-renewable source. A typical example is crude oil. However, fuel can also come from renewable sources, which can be considered infinite, such as solar power. (In fact, non-renewable fuels are renewable as well.

Only the time required for the process of "growing" fossil fuel is millions of years, making them non-renewable in practice.)

- Feedstock energy is, for instance, contained in materials, which are produced from fossil fuels that are used as a material. This type of feedstock energy is non-renewable, just as the fuel itself. Conventional polymers are the principal example in this context. Feedstock energy is, on the other hand, also contained in naturally grown, renewable materials, such as woods. These are, at least in theory, available for an infinite time.

None of these resource aspects is taken into account in the OPM because expressing resource depletion aspects in combination with environmental emission aspects isn't possible, as both aspects are of different nature. (Resource depletion relates to the input-side of a system, while emissions relate to its output-side, see chapter 2). Considering resource aspects could only have been accomplished by means of a second indicator, e.g. a 'depletion indicator' or a 'recyclability indicator'. (Such resource-related indicators are realised in methods such as MIPS and EDIP, see chapters 3 and 5.)

Having two or more indicator scores as a decision basis, however, implies trade-off situations and these are exactly intended to be avoided by using a single score as a result (see chapter 4).

Thus, where feedstock energy is stated, this is only done in order to facilitate the quantification of environmental impact resulting from the materials production stage and the end-of-life stage of fuel-bearing (non-renewable and renewable) materials. Accounting rules in this context are explained in section 6.6.

Scarcity or abundance of fuels are not mirrored, either. This, however, would only result in an "amplification" of tendencies indicated by Oil Points. Those fuels, which are finite - namely fossil fuels such as coal, oil and natural gas - and which, therefore, could be attributed with a high 'depletion indicator' value are ascribed a relatively high Oil Point indicator already because they lead to emissions in combustion processes. Renewable fuels, in turn, would get a low 'depletion indicator' value (or even no value at all) and have a relatively low Oil Point indicator.

Recycling & re-use

Activities related to conservation of non-renewable resources like "recycling" and "reuse of materials" are mirrored positively in the OPM:

- Recycled material has a lower Oil Point indicator value (that is in materials production) than primary material. This lower value results from the lower amount of fuel energy required to produce the recycled material. This, however, is only relevant for metals not for polymers, as the energy requirement for re-melting of polymers is practically the same as for primary material.

- A typical example for substantially lower energy requirement in materials production is Aluminium. Primary Aluminium is about 20 times more energy-intensive than 100% secondary material.

- Re-used material has an OP indicator of zero as no notable amounts of fuel are required. Example for a re-used material may be a glass bottle, which is used as a candlestick in a second life cycle.

Renewable resources

Oil Point indicators for the feedstock share of renewable resources, such as wood, are subtracted in the materials production stage and added in the end-of-life, if incinerated or landfilled. This is based on the principle that amounts are added in that life cycle stage where an emission occurs. In practice, however, the feedstock share of renewable resources may also be left out in both stages.

6.5 Oil Points and environmental impact

Environmental impact and energy consumption

The basic prerequisite for using Oil Points for environmental evaluations is the fact, that contributions to environmental impact categories - especially to Global Warming - are *directly proportional* to consumed electrical, thermal and chemical energy whenever the production of this energy is related to the combustion of fossil fuels.

This is, in fact, the case *today* where more than half of all energy production is based on the combustion of fossil fuels - mostly for electrical energy and for fossil fuel-based engines (see chapter 2). The concentration on energy relationships alone, in turn, is justified by the fact that the energy consumption-related contribution to Global Warming is by far the biggest (human-induced) contribution to this impact category (see chapter 2).

The focus on the relation between energy requirements and environmental impact differentiates the OPM from Life Cycle Energy Analysis: In Energy Analysis, input and output of energy as such are in focus of interest and they are balanced. In the OPM, however, energy inputs and outputs of energy-carrying materials are used to approximately quantify the related environmental impact.

Condition for using energy consumption as indicator

The principal condition for using energy consumption as the *sole* indicator for environmental implication is the assumption that chemical aspects are negligible in the case at hand. A condition for using the OPM is the situation today. If the global production of e.g. electrical energy would be entirely based on renewable sources, e.g. wind power, the causality between energy consumption and environmental impact would not exist any more and the OPM could not be used any more for environmental evaluations.

However, as situation and development on the energy market are today, such a situation (unfortunately) cannot be expected to become reality in the next two decades, [WEC 00, IEA 98].

Furthermore, theoretical contemplations show that today’s energy demands - let alone the rising ones of the future - can by far not be satisfied by regenerative sources alone regarding today’s technological state of corresponding technologies [WEC 00], see chapter 2.

This makes Oil Points an appropriate indicator for environmental impact – today, as well as in the near future.

6.6 How does it work in general? – The three steps of the Oil Point Method

An Oil Point evaluation (OPE) is done in three steps, with three elements in each step:

Step 1: “FOCUS” Definition of
A: Goal,
B: Scope and
C: Functional Unit

Step 2: “EVALUATE” Evaluation by means of
A: Model of the product system,
B: Oil Point indicators and
C: Calculation of results

Step 3: “INTERPRET” Interpretation of the result with respect to
A: Assumptions and estimations made,
B: Holistic context and
C: Improvement potentials

The “OPM road map”

This procedure can be visualised in a 3x3-matrix structure, the “OPM road map”, shown in **figure 6.1** below. This map represents a simple aid to keep all relevant elements in an Oil Point evaluation in mind.

The road map accompanies also the instructions and case studies, which are described in the subsequent sections. Here, it facilitates a quick overview by indicating the current step in the margin on the left.

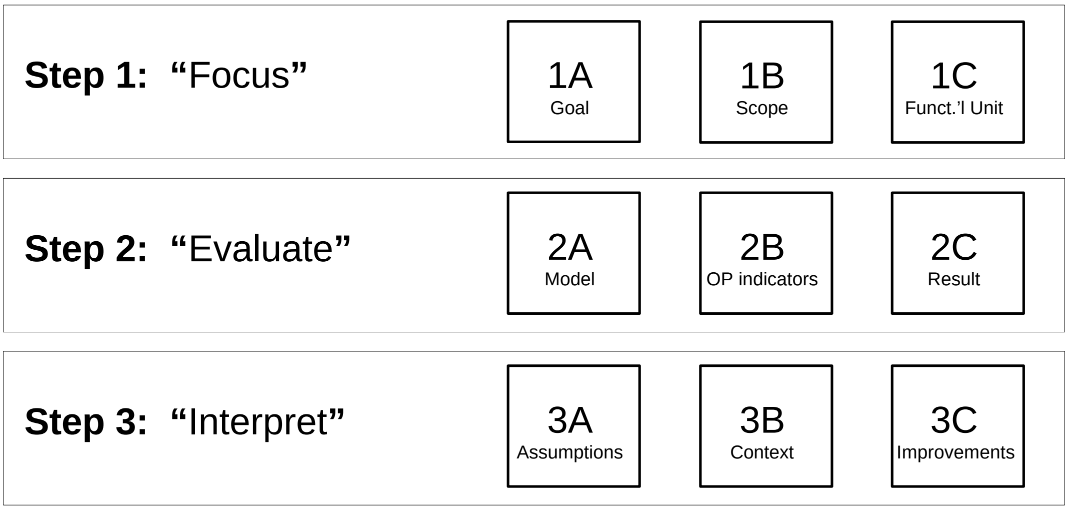


Figure 6.1 The three steps of an Oil Point evaluation and their elements illustrated in the “OPM road map”

Step 1: “Focus”

This step represents abbreviated Goal and Scope Definitions as known from formal LCA. The designer has to do three essential things here:

1A Define the *Goal*, i.e. the decision to be supported,

1B Define the *Scope*, i.e. the system boundaries
(in a technical, spatial and temporal way) and

1C Define the *Functional Unit*, i.e. the service, which the different solutions have to deliver (quantitatively, qualitatively, temporal and spatial)

1A Define the Goal (Decision to be supported)

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Environmental assessments can be used for two general applications:
- Analysis of a given product or service or
- Comparison of two or more competitive products or services (see section 3.X). In either application, the goal can be to support e.g.:

- decision-making in product development
- determination of legislative measures
- documentation of environmental performance for advertising

The OPM is only to be used in product development, as it is a rough tool and both legislative and documentation-related purposes require detailed approaches.

The type of decision to be supported by an Oil Point evaluation will typically be the “*determination of the environmentally superior material solution in the given situation out of a number of options”*. However, it can, for instance, also be the “*determination of environmental weak points in a given life cycle*”. Main aim of this point is to make the designer aware of what he or she tries to achieve with the evaluation – already from the start.

1B Define the Scope (System boundaries)

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Defining the scope consists first of all of defining the system boundaries in terms of the life cycle stages to be considered. The main question to answer in this Step of the OPM is thus:

- “Which life cycle stages shall be considered?”

Usually, all stages will be considered, i.e. materials production, manufacturing, all transport, use and end-of-life. In certain cases, however, focus may deliberately be put on only one stage: for instance “use”, if it is strongly expected that this stage is by far the most critical one. A comparison of two solutions could then only comprise the use stages of each solution.

Furthermore, the spatial extent of the product system has to be defined. The main question to answer in this context is:

- “In which countries do the stages of the life cycle take place?”

Such spatial aspects are not only to be considered in order to make aware of long or short transportation routes, but rather because of

– potentially different use-patterns and

– potentially different end-of-life scenarios

in many countries. These have influences on the assumptions made for product-modelling.

Use-pattern and End-of-life scenario

The average use-profile of a TV-set used in the UK, for instance, shows more intensive usage than the use-profile of the same TV-set used in Denmark (5.3 hours use per day vs. 4 hours, see [Wenzel et al 97], p. 393). The usage period and thus the lifetime of the product may also differ influenced by factors such as early failure due to intensive use, outdating of technology or even due to changed fashion.

Products with rapid technology development cycles, e.g. mobile phones in Japan, are an example for products, which are affected by the two latter factors.

Similarly, the end-of-life scenario may be different in different countries: in Germany, it may be recycling while in Denmark it may be landfill or incineration.

A short reflection about spatial aspects is recommended especially for **materials stage**, use stage and end-of-life stage as these stages usually turn out to be by far more important for the overall environmental performance of a product than manufacturing and transport (compare section 2.7).

Temporal aspects - concerning the length of the individual life cycle stages - may be important as well. The question to answer here is:

- “Which duration do the single life cycle stages have?”

The product system as such should be documented by drawing a simple model of the product system. (It is also mirrored in Step 2, where a table is filled out with processes comprised in this product system, see paragraphs on Step 2.)

In case of any doubt in a specific case, a worst case scenario should be assumed (at least for those stages where there is no doubt what that worst case probably is). For the TV-set this would mean “intensive use over a long period of time” and “incineration”.

1C Define the Functional Unit (Service to deliver)

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As described in chapter 3, the Functional Unit defines the service, which the product performs for the customer. It represents the basic scale for the comparison of the original product with other product solutions, in which e.g. different materials or different working principles are utilised. In the Functional Unit, the service has to be defined with respect to quantitative, qualitative, temporal and spatial aspects (Both temporal and spatial aspects have been defined in the scope, element 1B and are just repeated here).

In formal LCA, the Functional Unit is defined in the Scope Definition, see [ISO 14040], p. 5. However, as the Functional Unit is *the* scale for any environmental comparison, it is such an important part of an environmental evaluation, that it is included as a separate element in the OPM.

For a coffee machine, for example, the four aspects of the Functional Unit could be:

- quantitative aspects:
  - Number of cups that can be brewed: e.g. 8, 10 or
    maybe 12 cups
- qualitative aspects:
  - Brewing process adjustable for few or many cups
  - Colour and surface finish of the machine:
    e.g. red, black or silver, respectively dull or shiny metallic
- temporal aspects:
  - Expected total length of the life cycle
  - Expected use-pattern (e.g. frequent or occasional use)
- spatial aspects:
  The countries of production, usage and especially disposal

Step 2: "Evaluate"

In comparison to formal LCA, this step can be considered to be a largely simplified combination of an input-oriented Inventory and an exclusively energy-related Impact Assessment. The procedure to follow is common for all indicator-based methods. The step comprises three elements, which the designer has to perform:

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2A *Model* the product system,

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2B Fill in *quantities and OP indicators* and

2C Calculate OP figures, OP sums and the *OP result*

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In this step, the designer fills out a table, where he or she lists all processes known and/or assumed to happen in the life cycle stages. With this model of the product system, the designer looks for respective Oil Point indicator values in the list provided in Appendix I. Indicators, which are not included in this list may be estimated or retrieved from other sources (see section 6.7).

The Oil Point indicator values are multiplied with respective quantities, which are known and/or assumed to occur in the life cycle. Finally, the Oil Point sums are added-up to a single figure, the Oil Points result. Certain rules for accounting of different kinds of materials and end-of-life routes have to be observed. These rules are given in section 6.6.

The procedure will be explained further by means of an example in section 6.8.

Step 3: “INTERPRET”

This step requires the designer to do three things:

3A Check the importance of *assumptions and estimations* (sensitivity)

3B Check the result in a *holistic context* and

3C Seek *improvement potentials*

3A Check the importance of assumptions and estimations (Sensitivity)

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Environmental evaluations always involve a number of factors, which are unknown but which may have a substantial influence on the overall result of the evaluation. Obviously, this is especially true for evaluations at the design stage of future products. As this circumstance is inevitable, any environmental evaluation has to include a check, whether result and conclusions would change significantly, if estimated or assumed values were different. Such a check is described here, as element 3A of the OPM. The point is to find out, how reliable and trustworthy the result is.

In formal LCA, e.g. the EDIP method, the procedure of re-checking results is called “Sensitivity Analysis” and is performed after the Impact Assessment phase (compare chapter 3).

Types of unknown factors

There are two principal types of unknown factors affecting environmental evaluations at the design stage:

- Those concerning the model of the product system as such, (e.g. processes included in the life cycle stages, life time, use-pattern, end-of-life scenario) and
- those concerning parameter values, i.e. data, used within the model (e.g. the electricity consumption of an appliance, the total transport distance)

Constraints

For the effort put into a sensitivity check it is important to be aware of the fact that it may not be possible to determine certain factors, but that it may well be possible to determine certain others, if appropriate sources can be found. The use-pattern, for instance, has to be assumed in any way, whereas realistic data for the electricity consumption in manufacturing probably can be retrieved, e.g. from a producer.

Procedure

In order to check sensitivity, estimated parameter values and assumed scenarios have to varied in extreme but still realistic ranges - that could be halving or doubling values or assuming “worst cases” respectively “best cases”. While doing so, it has to be monitored whether or not the overall result changes significantly. Those parameters, which do have a large influence on the overall result are called “key parameters”.

Key parameters

In principle, this check should be performed for all assumptions, i.e. those concerning the origin of the materials (e.g. primary or recycled), the manufacturing route, the transport distances, the use-pattern and the end-of-life path. Manufacturing and transport, however, often play such a minor role in the overall result of environmental evaluations, that efforts usually can concentrate on the stages materials production, use and end-of-life.

When analysing a coffee machine for instance, any change in the use-pattern (e.g. the number of times the machine is used and the average number of cups brewed) is likely to be found most crucial for the overall result, as each use triggers electricity consumption etc.

Questions to answer

The questions to be answered in the sensitivity check are therefore:

- “Which are the key parameters?”
- “Are the estimated values for the key parameters realistic?”

Sensitivity in a rough method

The OPM is a rough method. Therefore, the question may arise, whether a sensitivity analysis makes sense at all. The first result could be accepted as it is. Why re-checking estimates and assumptions, which were made as good as instantly possible already the first time? The answer is, that, provided a low level of experience in environmental evaluation, only such a re-check can reveal the importance of a single estimate or assumption for the overall outcome. What is more, the individual who performs the evaluation finds out at which points further effort, e.g. for more specific information, is needed and where not in order to make the result trustworthy. Such knowledge about the reliability of a result is even more important in a method for *early* design stages. Therefore, it was decided to include a sensitivity check in the OPM.

3B Check the result in a holistic context

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This element is most important as it is determined here, whether an effort for environmental improvement of the specific product makes sense in the first place, or whether efforts should rather concentrate on something else. In this way, the relative importance of the decision is clarified further.

Production volume

In the case of a coffee machine, the interpretation could lead to the awareness that not only the consumption of energy and coffee during use are crucial negative environmental factors. Also, such machines are present in virtually every household and that, therefore, even a minor improvement on each single machine could lead to significant overall improvements due to the high production volume. (see fig.2.1, p.15)

An important question to answer in a holistic context is, therefore:

- "How large is the production volume?, i.e.
  How many of these products are produced, e.g. per year?"

Part of a more complex product?

When deciding upon a material to be utilised in a more complex product - say, the material for a car door - it is important to look at the product as a whole at this step, i.e. in the example: on the whole car.

Thus, also *product complexity* or *"part-of relationships"* should be among the issues considered here. This aspect is considered by answering questions such as:

- "Is the examined product part of a larger system/product?

And, if it is

- "How important is the performance of the examined product for the environmental performance of the whole larger system/product?"

Improvement potentials

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3C Seek improvement potentials

Depending on the outcome of element 3B, improvement potentials should be sought:

1. In the larger product or system, if the examined product is part of it
2. In the product itself, if it is not part of a larger system

For a car door, for instance, being part of the larger product "car", priority should be set on improving the environmental performance of the car. Weight reduction in order to reduce fuel consumption and thereby reduce environmental impact of the car as a whole is one appropriate means. The importance of a holistic contemplation is also shown in a case study on materials for window frames in section 6.8.

(Setting "Weight reduction" as the major target of environmental effort is actually common practice in automotive industry [Kind 00, Diener 98]. An LCA of car underbody parts, however, revealed that an increased total weight of the vehicle can still lead to the most fuel-saving solution. In the specific case, this was due to the substantial improvement in the aerodynamic behaviour resulting from the utilisation of weight-adding underbody parts, see [Liechti/Nyborg 98])

Seeking improvement potentials in the product itself is most effectively done, by determining the stage with the highest Oil Point sum (i.e. the highest impact). The origin of this high value, e.g. the necessity of drying of some natural material, can then be found and alternatives can be developed and checked again. In principal, it is up to the designer, how many of such improvements should be sought. Often, however, a substantial improvement will already be achieved by tackling the one or two largest sources of impact.

6.7 Materials accounting rules in the OPM

In principle, calculations in the OPM follow the way of other indicator-based methods: A quantity, e.g. of a material, is multiplied by the suitable OP indicator. The result of this multiplication is an OP figure. All OP figures of one life cycle stage are added up to an OP sum. All OP sums are, in turn, added up to the OP result (see paragraphs describing Step 2).

Focus on energy-bearing materials

The OPM focuses on energy-related impacts on the natural environment. Although resource depletion aspects of materials are not regarded, it is still of great interest, how to account materials, which are energy-bearing. As they can “absorb” or “release” the most important greenhouse gas CO_2, they may increase or reduce the total energy-related impact. “Release” of CO_2 is always combined with a combustion process in which the material is used as a fuel. The term “fuel-bearing” material is therefore appropriate and generally used.

There are different kinds of fuel-bearing materials and also different end-of-life routes for them. This means, that accounting rules have to be defined in order to make calculations unambiguous.

It could make sense to distinct materials after “CO_2 absorption capability”. CO_2 is, however, rather only the carbon of the carbon dioxide, which is bound in the fuel-bearing material. The distinction should thus reflect whether the fuel-bearing material can cause a net increase of CO_2 in the atmosphere - namely in case of incineration - or not. Fuel-bearing materials are, therefore, separated into:

- **Potentially CO_2-increasing materials**,
  i.e. materials that can cause a net increase of CO_2 in the atmosphere (e.g. conventional plastics that are incinerated) and
- **CO_2-neutral materials**,
  i.e. materials that can not cause a net increase of CO_2 in the atmosphere (e.g. woods)

In principle, these materials could be distinguished further into *primary* and *recycled* origin.

The other criterion of distinction is the end-of-life scenario for these materials. Options are:

- incineration (i.e. recovery of thermal energy)

- landfilling
- recycling (i.e. recovery of the physical matter, either with or without re-melting)

The way of accounting energy-bearing materials followed in Energy Analysis is to account the whole energy content (i.e. fuel and feedstock energy) in the beginning and - in case of incineration - to subtract released energy (i.e. feedstock) in the end [Boustead/Hancock 79]. If the material is not incinerated, its energy content remains in the system. For product systems, this results in a balance of incoming and outgoing energy. The difference between incoming and outgoing is the energy transformed in the system (e.g. to carry out work) or stored in the system. The same procedure of accounting is followed in LCA, see [Wenzel et al. 97].

All renewable materials can be incinerated and are thus energy-bearing. Some non-renewable materials, such as fossil fuels, can be incinerated, some cannot, such as metals. Some sort of credit should be given to recycled material.

Accounting in that stage where the damage occurs

For the OPM, it was decided to follow an overall principle of “accounting in that stage where the damage occurs”. A score - irrespective of whether it is a single OP figure, an OP sum or the overall OP result - should be higher, the more environmentally damaging the related process or product is. *This accounting practice is, therefore, different from classic Energy Analysis.*

All materials, which contain *fossil* carbon, such as polymers, are not accounted with their total energy content (i.e. fuel and feedstock energy together) but only with that share, which actually causes emissions in the materials production stage: the fuel energy. If such materials are landfilled, they are not accounted in the end-of-life stage at all, as their feedstock energy content and thus the fossil carbon content, is not released over a reasonable period of time, e.g. 100 years. *(A problematic issue for biomass materials is here, however, methane generation on the landfilling site, as methane is a 25 times more serious Global Warming gas than carbon dioxide, seen over the typical time horizon of 100 years, see (Wenzel et al. 97], table 10.3, p. 99.)* Accordingly, the feedstock energy share is *added* as an Oil Point value, if the fossil carbon-containing material is incinerated. Credit is also given for ‘recycled’ material and non-fossil carbon-containing, i.e. natural material.

The accounting rules in the OPM for all three kinds of materials and all end-of-life options are shown in **table 6.2** and **6.3**.

Potentially CO_2-increasing materials, e.g. conventional plastics (primary or recycled)

End-of-life option		Incineration		Landfilling		Recycling	
		Fuel	Feedstock	Fuel	Feedstock	Fuel	Feedstock
	Materials Production	+	0	+	0	+	0
	End-of-life	0*	+	0*	0	0*	0**

Table 6.2 Accounting rules for potentially CO_2-increasing materials, such as conventional plastics, for different end-of-life options. Accounting rules are similar for primary and recycled source material, although weight loss in recycling has to be observed.

Remarks: + : The OP figure is accounted positive,
0 : The OP figure is not accounted,
* : End-of-life processes require fuel as well. This, however, is accounted for in the stage “All transport”,
** : Loss of material occurs during recycling (e.g. 20 wt. %).

This accounting scheme is valid for conventional oil-based plastics as opposed to recently developed e.g. starch-based plastics. ([Wenzel et al. 97] p. 245)

CO_2-neutral materials, e.g. woods

End-of-life option		Incineration		Landfilling		Recycling	
		Fuel	Feedstock	Fuel	Feedstock	Fuel	Feedstock
	Materials Production	+	0	+	0	+	0
	End-of-life	0*	0	0*	0**	0*	0

Table 6.3 Accounting rules for CO_2-neutral materials, such as woods, for different end-of-life options.

Remarks: + : The OP figure is accounted positive,
- : The OP figure is accounted negative,
0 : The OP figure is not accounted,
* : End-of-life processes require fuel as well. This, however, is accounted for in the Transport stage,
** : Methane can be generated in landfilling

The accounting scheme of table 6.2 is valid for all plant-based materials as they only “release” that amount of CO_2, which they have “absorbed” during their growth.

(In principle, cultivated and naturally grown CO_2-neutral material could be separated because a cultivated plant could be considered a net reduction of volatile CO_2 as long as the plant lives.

A massive cultivation of e.g. trees would then reduce the amount of CO_2 in the atmosphere substantially. Utilisation of recycled wood, e.g. for chipboards could also be accounted separately. Both is not suggested here in order to keep the accounting principle as uncomplicated as possible.)

6.8 “One page description” and abridgements

The description of the OPM given so far does not necessarily indicate that the method will be quick in application, which after all is one of the main ambitions with the method. Therefore, a “one page” description was prepared. That short description would be the basis for individuals for making evaluations. This “one page” description of the method is given in Appendix II.

In practice, the procedure may also be shortened:

- Some elements may be similar in different OPEs. For example, the element 1A “Goal”, will usually be materials selection.
- Sometimes, certain elements may be deliberately left out by the designer, e.g. element 3C, if only a first impression of the environmental performance is sought.
- Routine with applying the method, especially in defining a Functional Unit and modelling product systems will also shorten the application.

Time requirement

Bearing in mind the rough character of the method, an evaluation of a typical consumer product will take about one hour or less for a first iteration.

6.9 How does it work in detail? - Example: Environmentally-conscious materials selection for a window frame

In the following sections, the three steps of the procedure shall be explained by means of an example product: a window frame. Typically, such a frame could be produced in wood or in PVC-plastic with a steel core. (Data used in this example origin from a full LCA, where most of the data had been provided by companies, see [Bey et al. 97].)

Step 1: FOCUS

The first step in the OPM is to focus on the problem at hand. This is done by defining the goal of the evaluation, its scope and the Functional Unit.

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1A Define the Goal (Decision to be supported):

“Determination, whether or not wood is a preferable material for a window frame compared to PVC with steel core.”

1B Define the Scope (System boundaries):

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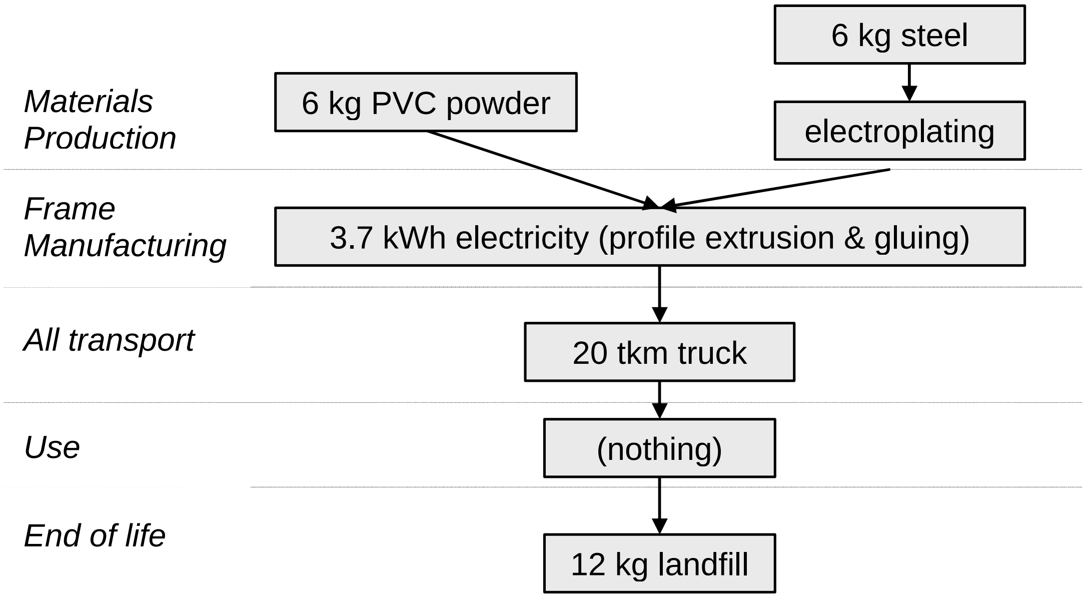
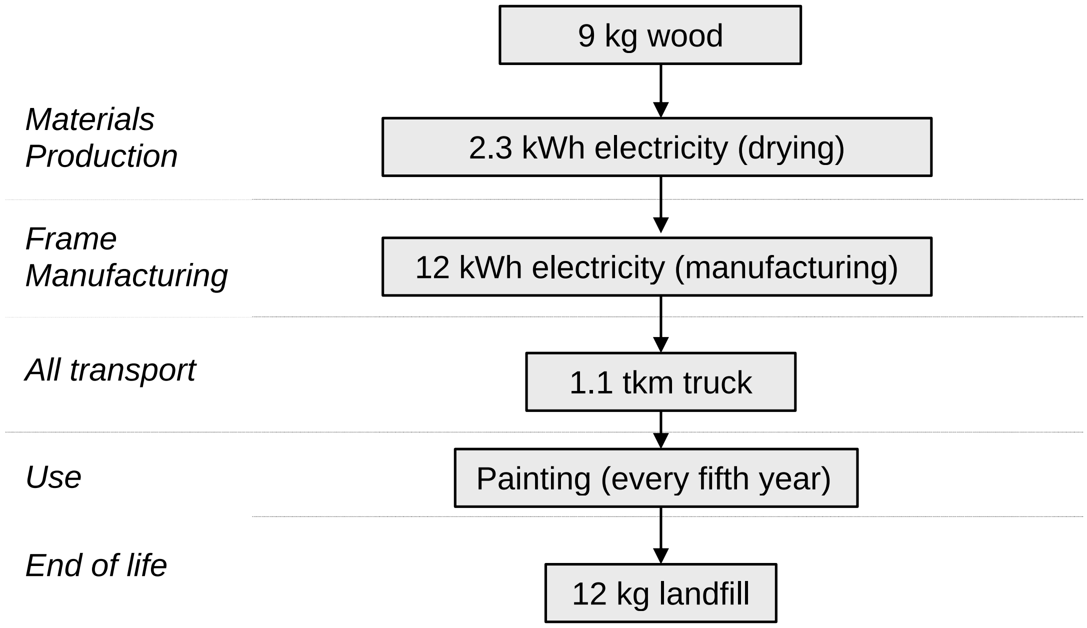
Standard manufacturing technology, wood from Scandinavia, PVC powder and electroplated steel profile from Germany, use and disposal in Denmark.

A simple model of the product system for the **PVC/steel frame** is outlined below.





A model of the product system for the **wooden frame**

Neither the glass pane nor the assembly materials (screws, bolts, etc.) are considered as they can be assumed to be similar for the two alternatives. The comparative result is thus not influenced by them.

1C Define the Functional Unit (Service to deliver):

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The Functional Unit could be defined like this:

“Supply of a non-openable frame for regular double-layer window panes, with the size of 120 cm x 120 cm (standard format), used and disposed-of in Denmark. The frame is required to stay in physically and visually good condition over a life time of 40 years”.

Step 2: EVALUATE

This step produces a quantitative result in the form of an overall score for each product solution. The results are achieved by modelling the product system, multiplying Oil Point indicators and quantities and calculating a result.

As an estimate, the solution in plastic consists of roughly 6 kg PVC plastic and about 6 kg electroplated steel profile. The wooden frame mainly consists of about 9 kg wood. Production waste is considered by choosing the quantities a little (e.g. 10%) higher than expected in the final product. Electricity consumption and transport distances are estimated (see App. II). As the frames are used and, especially, disposed of in Denmark, where incineration of PVC and impregnated wood is forbidden by law and a recycling system for PVC does not exist, the frames are neither incinerated nor recycled but probably disposed of on a landfill-site.

With this information at hand, a table like **table 6.4** can be filled out.

The procedure is relatively straight-forward and requires the designer to

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2A Model the product system,

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2B Fill in quantities and OP indicators

2C Calculate OP figures, OP sums and the OP result

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This procedure is similar to other indicator-based methods.

Life cycle stage	Material or Process	Quantity	OP indicator	Result
Materials production	PVC powder, primary (fuel share)	6 kg	0.8 OP/kg	4.8 OP
	steel profile, electroplated	6 kg	0.7 OP/kg *	4.2 OP
Manufacturing	electricity	3.7 kWh **	0.25 OP/kWh	0.9 OP
All Transport	truck transport	20 tkm	10 OP/1000 tkm	0.2 OP
Use	-	-	-	0 OP
End-of-Life	landfilling	12 kg	-	0 OP
			TOTAL (rounded):	**10.1 OP**

Table 6.4 Calculation of Oil Point figures for the quantification of potential environmental impact, shown by means of a PVC window frame

Remarks:

* : The OP indicator for electroplated steel profile is an estimate based on the one for “steel plate”, which is 0.4 OP/kg.

** : The electricity consumption for plastic manufacturing processes is about 10 MJ/kg or 0.2 OP/kg [see App. II]. Processing 6 kg PVC powder would thus account for 1.2 OP. In this case, however, more specific data were available from a full LCA involving company-specific data, see [Bey et al. 97]. The value of 3.7 kWh for the manufacturing stage, as stated in that source, is used here.

Estimations

Estimations based on data from literature or on experience are explicitly allowed in the method.

The complete calculation for the wooden frame is shown in **table 6.5**.

Life cycle stage	Material or Process	Quantity	OP indicator	Result
Materials production	wood (fuel energy)	9 kg	0.2 OP/kg	1.8 OP
	electricity (for drying)	2.3 kWh	0.25 OP/kWh	0.6 OP
Manufacturing	electricity (processes)	12 kWh	0.25 OP/kWh	3 OP
All Transport	truck transport	1.1 tkm	10 OP/1000 tkm	0.011 OP
Use	painting	-	-	0 OP
End-of-Life	landfilling, wood	9 kg	-	-
			TOTAL (rounded):	**5.4 OP**

Table 6.5 The Oil Point result for the wooden window frame

Step 3: INTERPRET

Sensitivity, holistic context and improvement potentials

In this last step, the sensitivity of the result should be checked very briefly – in order to determine, whether one can “trust one’s own result”. It should then be considered whether the product will be part of another system, because this may clarify the importance of the decision in a more holistic context. Finally, improvement potentials should be sought for.

3A Check the importance of assumptions and estimations (sensitivity)

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Almost any environmental evaluation requires estimations and assumptions. As this cannot be avoided, a sensitivity check is needed.

In the example of the PVC window, the OP indicator 0.7 OP/kg for the electroplated steel had been estimated (see table 6.1). If this value would be halved, the total result would be about 10 OP, respectively over 18 OP, if the value was doubled. Such extreme changes, however, would still not influence the overall result, because “wood” with its 4.5 OP would in any case stay preferable. Other estimations would be checked in the same way.

The utilisation of primary plastic material was an assumption. As can be seen in Appendix II, the Oil Point indicator of 1.5 OP/kg for PVC powder consists roughly of one half “fuel” and one half “feedstock” energy. If recycled plastic material would be used instead of primary, only the “fuel” part would be necessary. While the primary PVC material accounted for 9 OP, the recycled PVC would thus only require about half of this energy, i.e. 4.5 OP.

In a “best case” scenario (with the low value for electroplated steel and with recycled material), the PVC frame would score almost 8 OP.

Only if the electricity consumption for producing the wooden frame would be about twice as high than calculated, the wooden frame would reach this score. The electricity consumption is, however, considered to be realistic.

Transport distance could just as well be much higher in either of the alternatives without influencing the comparative result. In all scenarios, the plastic frame would be worse than the wooden one.

3B Check the result in a holistic context

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The window frame is indeed part of a larger system, namely usually the wall of a building. In this system, the window frame facilitates the support of a window pane by the wall. Seeing the window frame in this context and examining the overall environmental performance briefly, one may discover that the “environmental damage” caused by heat loss though the window pane is in the order of 100 times bigger than the one caused by either of the alternative solutions evaluated. The factor is the result of the following simple calculation:

15 litres fuel oil heat loss/year x 40 years lifetime = 600 litres fuel oil = 600 OP

Seen in this holistic context, the decision about the material for the window *frame* becomes basically irrelevant, while the insulation capacity of the glass *pane* becomes crucial.

Even if the additional amount of fuel oil due to heat loss was much smaller, e.g. 1 litre per year, the resulting 40 OP would still indicate the same conclusion.

3C Seek for improvement potentials

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The holistic contemplation would clearly lead to the conclusion to focus improvement efforts on the larger system, i.e. on the material of the window *pane*, or even on the whole system of wall and opening for light and air inlet, rather than the material of the *frame*.

A bar chart diagram with the results of tables 6.2 and 6.3 is shown below (**fig. 6.2**).

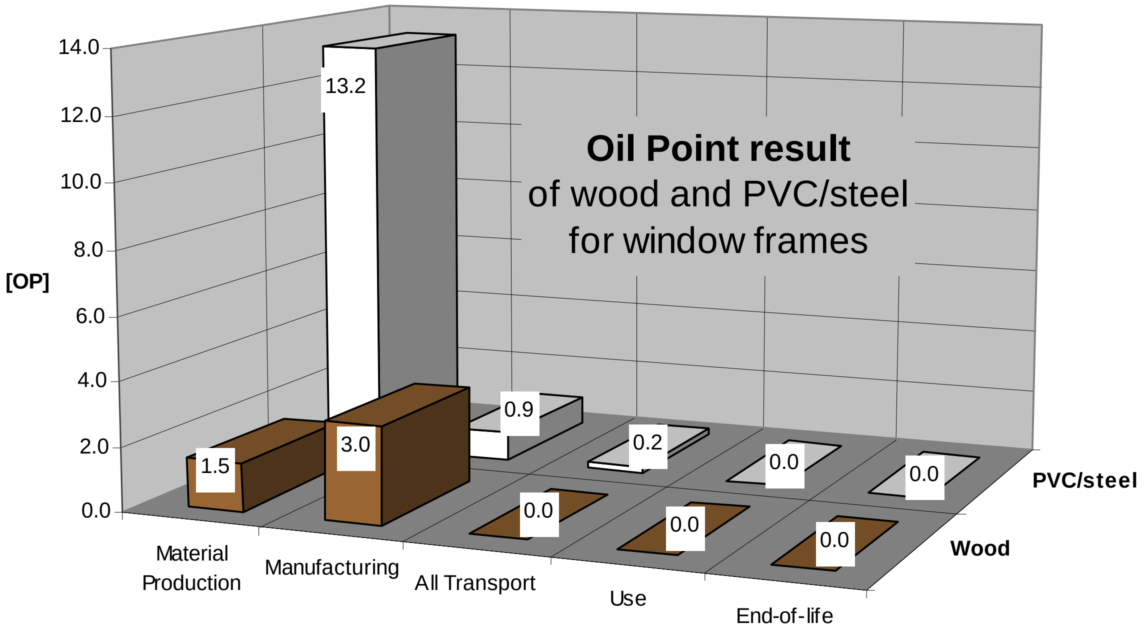


Figure 6.2 Comparison of window frames in wood vs. in PVC with steel core by means of the Oil Point Method

For this example, data had been partially derived from a comparative full LCA conducted earlier (see also the related case study in Chapter 7).

For the general application of the Oil Point Method, however, a number of Oil Point indicators had to be derived from energy data sources. Procedure, constraints and results of this process are described in the next section.

6.10 Data for Oil Point evaluations

6.10.1 Aim with the derivation of Oil Point indicators

The Oil Point Method is meant to be used by designers, who do not possess background knowledge in environmental assessment but who want to have a general impression of the environmental consequences, which are related to material options they have during their work, especially in early design.

Detailed specifications about the exact type of material and involved processes or shapes may not exist at this time and the alternatives may rather be to choose between plastics and wood for a solution, or to compare a solution in light metal with one in steel. Here, Oil Point evaluations are suggested to give the designer the required basis for decision-making.

How specific should Oil Point indicators be?

It is, therefore, not important to define Oil Point indicators (OPIs) for very specific materials, e.g. for a certain stainless steel, but rather to provide indicators, which are *generally valid* for the type or even the class of material (see **table 6.6**). (An even higher aggregation at “kind”-level doesn’t make sense, especially not for the purpose of materials and process selection.)

The ultimate target could thus be to define indicators at “class”-level, i.e. for each material class and for each other class of life cycle process. As this research underpinned, such an aggregation is possible for manufacturing processes, for transport and for end-of-life processes. For materials, however, an aggregation at class level is not feasible especially due to the variety of highly distinct metal alloys and various polymers existing today, which all have unique properties.

Kinds of LC processes	Classes	Types	Sub-types
Materials (processes of materials production)	Metals	Steels	- Stainless steel - Mild steel - …
		…	
	Polymers	Polyethylenes	- HDPE - LDPE - …
	…		
Manufacturing processes	Casting	Metal casting	
	Cutting		
Transport processes			
	…		
Use processes			
End-of-life processes	Incineration	Incineration of polymers	
	Landfilling		

Table 6.6 Hierarchy of terms *kinds, classes, types* and *sub-types* and focus on *types* for definition of Oil Point indicators (grey)

"Use" processes – if specified at all in a source - are usually expressed as consumption of e.g. electricity. This stands in deep contradiction to the actual importance the use stage has in many product LCAs.

Thus, indicators will be defined for the most important *types* of materials. For all other kinds of life cycle processes, however, it is aim to only derive one Oil Point indicator each. Furthermore, some typical use processes will be defined.

6.10.2 General conditions for data in Oil Point evaluations

The general conditions for data used in Oil Point evaluations are circumscribed by the overall aim of making Oil Point evaluations: This aim is to *roughly* determine the environmental performance of a material solution. In this context, the term "roughly" means:

- "Revealing a major part of the total potential environmental load related to the solution" and
- "Ideally, leading to the same material-related decision as a formal LCA would do" (in all case studies, the EDIP method was used as such a reference).

In the previous chapter, energy-related conditions - in the way they are today - have been determined as a suited indicator for environmental impact in the context of such rough evaluations.

Missing data

A typical problem in environmental evaluation is lack of data. On an overall level, this problem is treated in the OPM by utilising energy data, i.e. data, which are available from many sources and which – most importantly - can be estimated if necessary.

Poor data and "wrong" decisions

An overall constraint is to avoid "wrong" decisions due to poor data. In general, however, two kinds of sources of "errors" leading to "wrong" decisions have to be separated:

1. Errors introduced by poor data leading to wrong Oil Point indicators and
2. those introduced by wrong modelling, calculating or interpretation.

While the former type of errors could be introduced by the author and is thus called "definition-related", the latter kind is introduced by the designer, termed "application-related".

The course of getting Oil Point results and potential stages and sources for the introduction of errors are shown in **figure 6.3**.

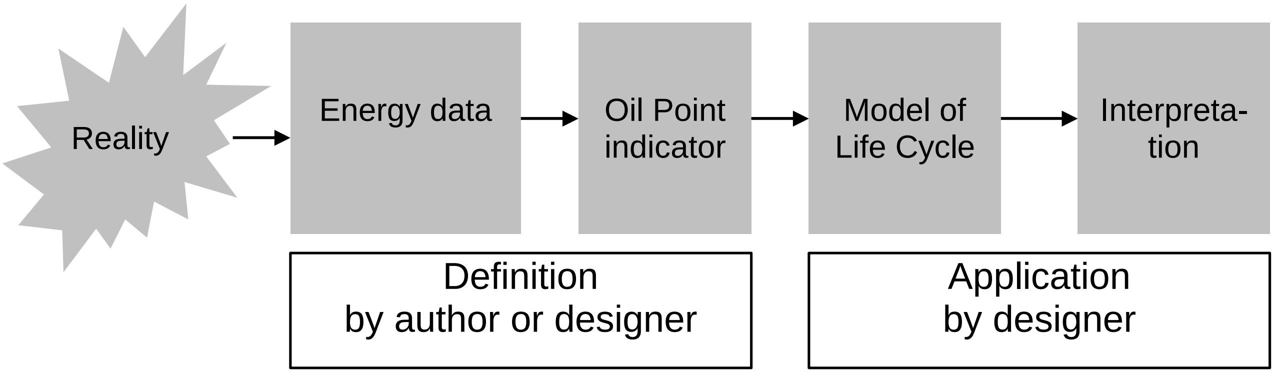


Figure 6.3 Sources for the introduction of deviations from the real situation in the result of the evaluation

Application-related problems are tried to be minimised by allowing simplified modelling, avoiding long decimal figures and providing examples for overall interpretations.

Nevertheless, it lies in the nature of environmental assessment that subjective aspects have an influence at many levels (the modelling of the product system, for instance and of course interpretation) because decisions have to be made *case-specific*. It is, in principle, always possible that two different persons come to two different conclusions.

What to do?

The definition-related problems are treated by using well-established data sources and by following certain rules for defining Oil Point indicators. This is described below.

In order to minimise overall "errors", those introduced by the author are minimised. This was accomplished during the definition of Oil Point indicators, by using energy data from recognised sources (see section 6.10) and by using *typical* values as basis for the definition. Furthermore, the data have been left transparent by stating the range of values found in the sources.

6.10.3 Energy data in general

Energy data are averages

Energy data found in literature are almost always given as averages calculated from ranges between maximum and minimum values. The reason for this circumstance lies in the variety of parameters influencing the energy consumption of a given process. The energy consumption of steel production, for instance, depends highly on the type of furnace used and the mix of raw materials employed (bearing in mind the enormous variety of steel alloys produced). Other factors can be age of the plant or sheer method of measuring, i.e. collecting the data (see comments in [Boustead/Hancock 79]).

Many influencing factors

Energy values for “production of steel”, for instance, will vary a lot for individual steel alloys. Due to influences by local conditions, such as climate, even data on the same alloy will often be different from country to country and even from plant to plant and season to season.

This generic problem of determining energy data always has to be borne in mind when examining data on energy requirements for materials and processes.

6.10.4 Gross and Net Calorific Value

The gross calorific value, or high heat value, is the heat energy evolved when all of the products of combustion are cooled to atmospheric temperature and pressure as in a bomb calorimeter. The gross calorific value will therefore include the latent heat of vaporisation and the sensible heat of the water in the combustion products.

The net calorific value, or low heat value, is the heat evolved when the products of combustion are cooled so that the water remains as a gas. It is therefore equal to the gross calorific value less the sensible heat and latent heat of vaporisation of water. The magnitude of this deduction is 2.45 MJ/kg water condensed.

6.10.5 Crucial factors of energy data for environmental evaluations

As stated in the previous chapter, the relation between energy consumption and environmental impact is dependent on a number of factors. The most important ones are:

1. The way of producing (or rather *transforming*) the energy from fuels to e.g. electricity or heat
2. The overall efficiency of producing and delivering this energy (usually ca. 30 % but up to 70 %, see tables in section 3.5.3 and **figure 6.4**)
3. The share of overhead energy in manufacturing (e.g. 75 % for production of electromechanical products) (see cases in [Wenzel et al. 97]) and
4. The efficiency of the actual manufacturing processes, e.g. 60 % for a chip-taking manufacturing process [Schulz/Schiefer 98]

This context has to be kept in mind whenever energy consumptions are used as an indication of environmental impact (see details in section 5.7).

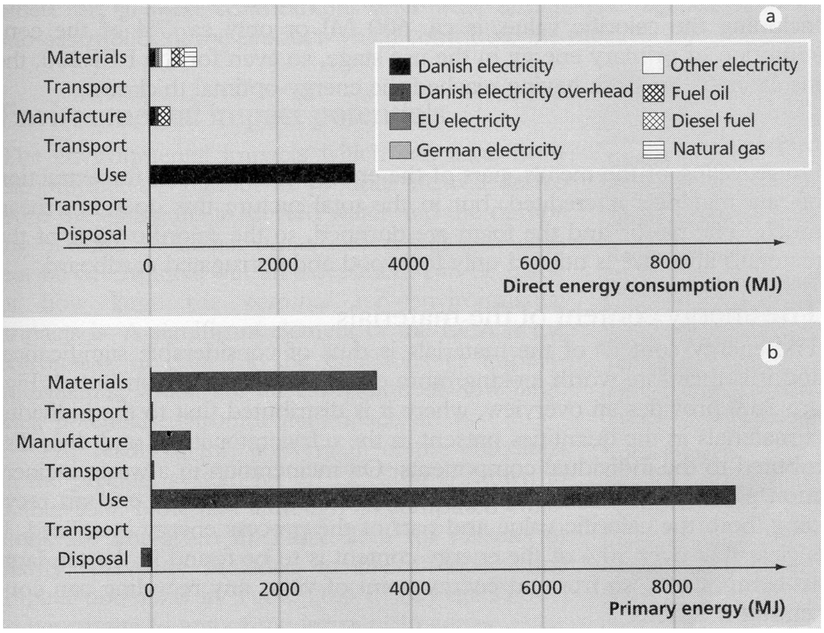


Figure 6.4 Energy profiles of a refrigerator:
upper part (a), The direct energy consumption expressed in MJ,
lower part (b), The related primary energy consumption after inclusion of energy efficiency (about 30 % on average) and calorific value, [Wenzel et al. 97], p. 333. It is such primary energy consumptions that are accounted in the OPM

6.10.6 Energy data for Oil Point evaluations

Determining the realistic *energy* consumption of a certain industrial process is one thing, deriving all *terminal environmental exchanges* (i.e. inputs from earth and final outputs to air, water or soil) related to this industrial process, however, another thing. The latter task is more complex but crucial in overall environmental assessments. For Oil Point evaluations (OPEs), however, this task is limited to the determination of the initial inputs of fossil fuels, such as coal, natural gas and oil.

Energy data for OPEs, therefore, have to include all systems and processes, which are necessary to conduct the respective industrial process. This means that especially processes for

- energy production (the share based on fossil fuels, not the share of nuclear fuels or regenerative sources),
- materials extraction and
- transport

have to be taken into account and that all inputs have to be traced back to their origin “in the ground” and all outputs have to be the total emissions of the whole system.

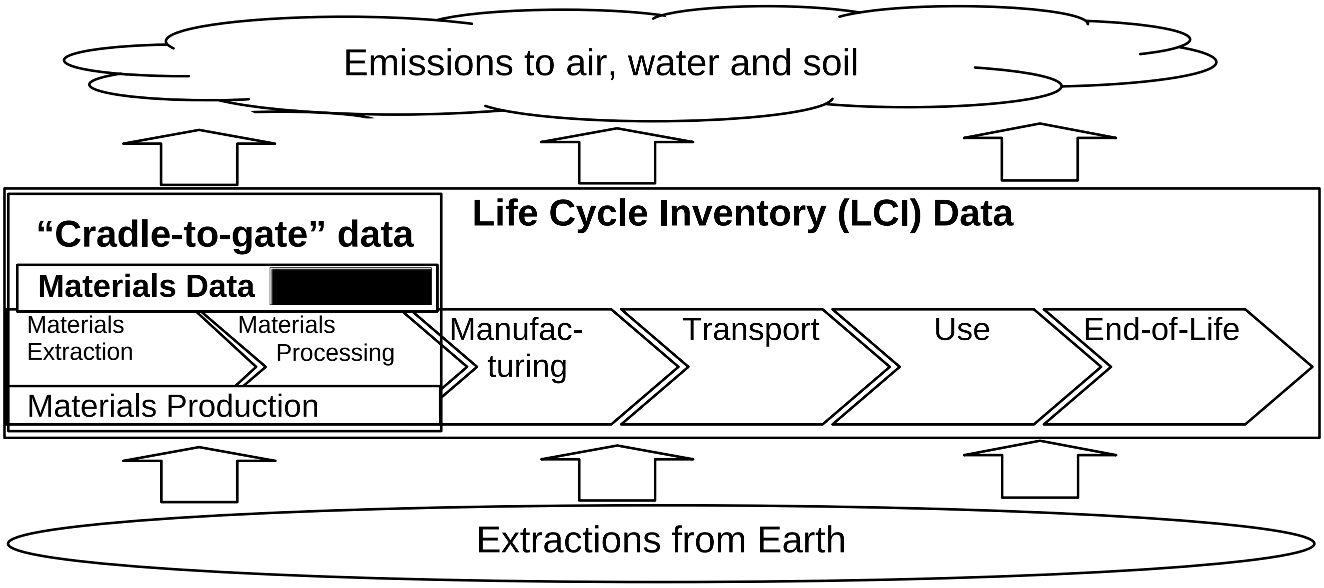


Figure 6.5 Distinction of *materials data*, which cover direct in- and outputs (maybe only related to materials extraction), *Cradle-to-gate data*, which cover terminal in- and outputs for Materials Production and *LCI data*, which cover terminal in- and outputs over the whole life cycle

"Cradle-to-gate" inventories

These additional factors are covered by so-called "cradle-to-gate" inventories. Cradle-to-gate inventories give a complete picture of all the *terminal* resource consumptions and environmental emissions related to the production of a certain material in a form, in which it would be delivered to the "gate" of a hypothetical manufacturing company. This is sketched in **figure 6.5**. Energy data for OPEs should be extracted from such cradle-to-gate inventories.

Separation of fuel and feedstock energy of materials

Energy data of those materials, which have a calorific value and which therefore could be used as a fuel – typically plastics and natural materials -, should specify "fuel energy" and "feedstock energy" separately. This separation is relevant for the consideration of recycled materials and for accounting in the "End-of-life" stage (see tables 6.1 and 6.2).

6.10.7 Data quality in the context of Oil Point evaluations

Similar to the classification of data used in LCA, energy data for OPEs are categorised after two parameters:

- Their *specificity* (ranging from "product specific" over "site-specific" to "general" data) and
- their *source type*, i.e. the way of their collection (ranging from "measurements" to "unknown" or "non-qualified estimates", also referred to as "reliability", compare section 3.17).

Both parameters can influence an energy value significantly.

“Specificity” and “Method of collection”

The highest quality have data, which are “specific for the product evaluated” and, which have been “measured” directly in the factories producing the product. However, considering the enormous effort related to the collection of such data, the highest *practical* data quality to obtain is data from operating companies concerning the processes.

Concerning energy production, transport systems and other parts of infrastructure, data from statistical agencies and branch associations are preferable.

“Age” of the data

Besides “specificity” and “method of collection”, a third parameter is of interest for energy data in OPEs because it can have a considerable influence: the age of the data. Processing in general as well as transportation happen increasingly efficient and energy-saving.

Influences by technology

The magnitude of the “fuel” part of the overall energy requirement of materials is technology-related and is thus likely to decrease, the more recent technology is employed.

Even the feedstock share in the final product can change due to different practice of utilising material as process-internal fuel. PET resin, for instance, is stated in an APME report from July 1995 (and repeated in May 1997) to require about 38 MJ fuel energy and another almost 46 MJ feedstock energy. A later report from the same source, however, states the same energy values to be 38 MJ (fuel) and only 39 MJ (feedstock) ([APME 98], p. 11).

Original data, calculated data and duplicated data in data bases

A final factor of interest concerning data quality is their transparent presentation in data bases. A data base should always include clear information for each data set on, whether it was originally measured, calculated by the data base producer or whether data rather were duplicated unchanged from other sources. Stating own measurements and/or unchanged duplicated data are neutral ways of presenting data. Calculated and maybe standardised data have been influenced by the data base producer. Such an influence can be a great help for the user of the data base. Here, transparency in documentation and thus repeatability of what was done are very important. Otherwise the user can only rely on experience and capability of the database producer. It should, therefore, always be stated in such cases *how* this influence took place, e.g. by stating the standardising procedure and related calculations.

OPM energy data

As a consequence, sources for energy data used to derive Oil Point indicators should state

1. age,
2. specificity and
3. method of collection.

Materials data should furthermore

- be based on cradle-to-gate inventories and
- state fuel and feedstock energy of fuel-bearing materials separately

Restrictions in practice

Ideally, all data used for an evaluation should be recently collected, product-specific and measured. However, this is often neither feasible nor necessary. An OPM evaluation can – especially for first iterations – be based on general data or estimates for similar processes or technologies in order to get a rough overview.

Only if the sensitivity check (element 3A) reveals substantial uncertainties for one or more key parameters, more specific data have to be retrieved.

6.11 Data sources

Appendix I comprises more than 120 Oil Point indicators on life cycle processes concerning materials, manufacturing, transport, use and end-of-life. The data were collected from eight main sources: four reports respectively books and four software tools. These sources were:

1. Allen & Alting's four-volume set on "Manufacturing Processes" [Allen/Alting 86]
2. The APME "Eco-profiles" series of reports, e.g. [APME 97]
3. The BUWAL "Eco inventories for packaging materials", volume I and II [BUWAL 96a/b]
4. Boustead & Hancock's "Handbook of Industrial Energy Analysis" [Boustead/Hancock 79]
5. "Boustead Model 4" software [Boustead 98]
6. "Cambridge Materials Selector" software [CMS 97]
7. "EDIP LCV-tool" [EDIP 98]
8. "IdeMat 98" software [Idemat 98]

Additional sources were:

- Reports from producers and companies
- Reports from Environmental Protection Agencies (EPAs)
- Reports from research institutions

These sources were used due to their accepted use in current LCA work (sources 2-5, 7, 8), because they contain an enormous variety of energy data (source 6) or a compilation of very specific energy data (source 1).

Occasionally, additional sources were used e.g. for “CED values” (Cumulated Energy Demand) or “MI values” (Material Intensity) (see section 5.6). Especially “Cumulated Energy Demand” values were gathered from literature due to the lack of a publicly available database. (Due to similarities in the approach, a database with CED values would have been highly relevant for comparative reasons.)

All sources, extracted values and derived Oil Point indicators are given in Appendix I. The following sections describe the main sources with respect to their contents, age, specificity and way of collection.

6.11.1 Allen & Alting

Allan & Alting’s four volume set (about 770 pages in total) is a student’s manual which describes some 300 manufacturing processes in a uniform way. Each process is described by six basic frames. These frames contain process description, set-up & equipment, process schematic, typical tools & geometry produced, work piece geometry and characteristics of the process. For some processes, additional frames are provided describing the process with up to 24 frames. (see also section 4.3.3.).

Energy requirements of a process can be calculated from physical formulae and provided measured “unit power” requirements. Frames with energy data are only given for a fraction of the processes, primarily for cutting processes, here, however, in form of a table with different materials and hardness values (see **table 6.7**). Energy values can be calculated to MJ/kg of removed or processed material.

Power requirements for Drilling

Formula: Machine horse power [HP] = unit power x removal rate [in^3/min]

Material	Hardness HB	Unit power*
Aluminium	30 to 150	0.16
Brass	50 to 145	0.48
	145 to 240	0.8
Cast iron	110 to 190	1.0
	190 to 320	1.6
Mild steel	85 to 200	1.0
	330 to 370	1.4
	485 to 560	2.1
Stainless steel	135 to 275	1.1
	275 to 430	1.2
Plastics	N/A	0.05 (estimate)

** unit power based on: HSS drills, feed of 0.002 to 0.008 IPR, 80 % efficiency*

Table 6.7 Power requirements for Jig Boring, after [Allen/Alting 86], p. 64. An example is highlighted.

An example is given for drilling of mild steel with HB hardness of 330 to 370 and removal rate of 10 in^3/min, resulting in 14 HP. Taking a conversion factor of 1.34 HP/kW [Baehr 96] and a density of 7.9 g/cm^3, the energy consumption for drilling can be calculated to about 0.5 to 0.7 MJ/(kg removed material) (1.5 to 2.2 MJ/kg including an estimated 33 % efficiency of the electricity production.)

Manufacturing processes

The energy data given can be described as follows:

Source 1:	**Allen & Alting [Allen/Alting 86]**
Age	1986, thus relatively old
Specificity	The data are specific for processes, which are based on the same principle, e.g. cutting processes, casting or moulding processes, etc.
Way of collection	The values result from calculations. Physics formulae and values are given (e.g. for material hardness and necessary unit power consumption).

6.11.2 APME “Eco-profiles”

“Eco-profiles” is a series of reports (about 20 to 30 pages each) of the Association of Plastics Manufacturers in Europe (APME) with “cradle-to-gate”-inventories of the main groups of polymers, such as polyethylene, polypropylene, polystyrene, etc. Some other reports are dedicated to systems and infrastructures related to polymer production industry. There are about 20 reports available until now.

Due to their detail in documentation, these reports represent *the* major source for European polymer data and are often referred to for life cycle inventories (LCIs). The sources BUWAL, CMS, EDIP and IdeMat all use these data, as well.

The reports are being updated from time to time in order to reflect changes in industrial practice, thus later versions of a report may exist. Since only recently current versions can be downloaded from APME’s LCA-related Internet site (see *lca.apme.org* and Appendix VI). (Early reports of the series may be referred to in literature as “PWMI” due to this former acronym of the environmental unit of APME.)

The series is produced in association with Dr. Ian Boustead whose book and a software tool have also been used as a source to derive Oil Point indicators (see later sections).

As an example, an excerpt of a data set on “PET resin (bottle grade) is given below (**table 6.8**). (Each data set comprises seven additional tables, e.g. on required water resources, related air emissions, etc.).

Fuel type	Fuel Production & Delivery Energy [MJ]	Energy content of delivered fuel [MJ]	Energy use in Transport [MJ]	Feedstock Energy [MJ]	Total Energy [MJ]
Electricity	5.56	2.50	0.03	<0.01	8.10
Oil fuels	1.48	11.57	0.28	32.54	45.87
Other fuels	3.26	14.05	0.05	6.16	23.51
Total [MJ]	10.30	28.11	0.37	38.69	77.47

Table 6.8 Gross energy required to produce 1 kg of bottle grade PET (Totals may not agree because of rounding) [APME 99a], table 1, p.4. The fuel part of the gross energy requirement is encircled.

A general tendency documented in the APME reports is that the overall energy requirement for polymer products decreased slightly over the past years. Reasons for this tendency are probably reduced requirements for fuel energy for processing and more efficient technologies in general.

Description of the data (all reports):

- Fuel and feedstock are separated
- Data represent cradle-to-gate requirements

Polymers and related manufacturing processes

Source 2:	APME Eco-profiles e.g. [APME 97]
Age	1990 – today
Specificity	The data are averages of the processes at the operating companies
Way of collection	Data were provided by the operating companies, fuel & energy production data from Int. Energy Agency, transport etc. data from Boustead Model software tool

6.11.3 BUWAL “Eco inventories for packaging materials”

This source is a two-volume report by the Swiss Agency for the Environment, Forests and Landscape (BUWAL) with “cradle-to-gate” inventories of various packaging materials (and some graphic papers) on almost 600 pages. Packaging materials analysed include:

- aluminium,
- glass,
- plastics,
- packaging papers,
- corrugated/ non-corrugated cardboard,
- graphic papers and
- sheet steel

The study also includes information on related manufacturing processes, energy systems and auxiliary materials involved as well as on disposal of packaging material.

The source is very well-documented and transparent and, therefore, widely used for LCI work and databases.

The utilised 1996-edition (SRU 250), in German, represents a revised edition of a similar report from 1991 (SRU 132). All plastics data in the BUWAL reports are transferred from (earlier) APME reports (see previous section), but have been adapted to specific conditions of companies in the study. A revised and corrected edition of SRU 250 from 1998 is available in German, see www.buwal.ch/publikat/abstract/a429.htm.

An exemplary data set with energy data from the source is given on the next page.

Energy consumption: 1000 kg corrugated cardboard (blended 1)						
End energy carrier	**Energy for provision**	**Process end energy**		**Transport**		**Total**
	[MJ]	Quantity	[MJ]	Quantity	[MJ]	[MJ]
Electricity	3410	556 kWh	2000	26.6 kWh	100	5510
Biogas/ Manure gas	-	1.1 m3	20	- m3		20
Biomass	-	28.8 kg	490	- kg		490
Steam	390	1710 MJ	1710	- MJ		2100
Diesel	80	3.5 kg	160	7.5 kg	340	580
Natural gas	580	110 m3	4430	- m3		5010
Heating oil (EL)	60	7.6 kg	340	- kg		400
Heating oil (S)	290	20.7 kg	880	0.4 kg	20	1190
Wood	-	123 kg	2460	- kg		2460
Coal	0	0.1 kg	0	- kg		0
Total	4810		12490		460	17760
				Feedstock [MJ]		18410
				Overall total [MJ]		**36170**

Table 6.9 Energy requirement for the production of 1000 kg corrugated cardboard [BUWAL 96a], p. 54

Description of the data:

- Fuel and feedstock are separated for materials
- Materials data represent cradle-to-gate requirements

Several materials and related manufacturing processes

Source 3:	**BUWAL [BUWAL 96a/b]**
Age	1993 – 1995 (Energy and transport systems: 1990)
Specificity	The data are averages (e.g. over a year) of the processes at the operating companies
Way of collection	Data were provided by the operating companies and by respective branch organisations

6.11.4 Boustead & Hancock

The “Handbook of Industrial Energy Analysis” by Boustead and Hancock is divided into two parts: Part 1 (ca. 300 pages) describes principles and techniques of energy analysis and gives detailed examples of how these techniques may be applied in specific industrial cases. Part 2 of the book (ca. 100 pages) presents energy data for processes. Data are often given for different input forms, e.g. “Steel sheet from ore in the ground” or “Steel sheet from ore at the blast furnace” etc. Counting each input form separately, there are some 400 sets, otherwise, there are less than half as many.

It was an aim of the authors to present the data in a standard form, which – according to their comments - had been very difficult to accomplish due to poor documentation. (Today, some 20 years later, this is still very often the case!)

Although the source is aged, its strength lies in the generally successful attempt to present energy data in a standardised transparent way, which includes the fact that various comments are made on every single data set and the way of calculation is described.

Description of the data:

- Fuel and feedstock are separated
- Data represent cradle-to-gate requirements

Materials, auxiliary materials, related manufacturing processes and industrial systems

Source 4:	**Boustead & Hancock [Boustead/Hancock 79]**
Age	Before 1978, thus relatively old
Specificity	The data are averages for very specific operations
Way of collection	Mostly from literature

As an example, data sets for glass are shown below (**table 6.10**).

The eight sets refer to three processes. As mentioned earlier, the source contains about 400 of such sets.

System type	**Electricity**		**Oil fuels**			**Other fuels**			**Total system energy require-ment**	**Notes**
	Fuel production energy	Energy content of fuel	Fuel production energy	Energy content of fuel	Feedstock	Fuel production energy	Energy content of fuel	Feedstock		
GLASS from raw materials in the ground (MJ/kg)										
J	*	*	*	*	*	*	*	*	12.39	(1), (40)
J	*	*	*	*	*	*	*	*	18.24	(1), (42)
F	*	*	*	*	*	*	*	*	21.00	div.
H	(2.82)	(0.89)	(1.42)	(7.27)	-	(2.84)	(7.29)	-	(22.53)	div.
J	*	*	*	*	*	*	*	*	25.00	div.
F	3.16	0.99	1.58	8.09	-	3.16	8.11	-	25.09	div.
GLASS FORMING (MJ/kg)										
A	3.64	1.15	0.01	0.04	-	-	-	-	4.84	(4), (45)
GLASS MELTING (MJ/kg)										
A	0.44	0.14	0.19	0.92	-	-	-	-	1.69	(4), (45)

Table 6.10 Energy requirements of some processes related to glass production [Boustead/Hancock 79], p. 337. *System types*: “A” means “the main process only”, “F” and “H”: “includes several related systems, such as transport”, “J”: “is unspecified (in the original reference)”, *Notes:* references and comments

6.11.5 Boustead Model 4

The “Boustead Model 4” is a software and database for Life Cycle Inventories (LCIs) produced by Boustead Consulting Ltd. (UK). It contains over 2500 data sets on materials processing, e.g. paper products, containers and paints including sets on packaging and transport.

Data are highly specific and given e.g. for “Tinplate can production” separately for 100 ml, 330 ml, 440 ml and other sizes. About 80 data sets cover manufacturing processes.

The data are very detailed and continuously updated (though at a considerable expense for an end user license).

The data presentation is similar to the one used for the APME reports (see section 6.11.2).

Description of the data:

- Fuel and feedstock are separated
- Data represent cradle-to-gate requirements

Materials, auxiliary materials, related manufacturing processes and industrial systems

Source 5:	**Boustead Model 4 [Boustead 98]**
Age	Current, updated on a regular basis
Specificity	The data are detailed and given for very specific operations
Way of collection	Collected from operating companies by means of questionnaires

6.11.6 Cambridge Materials Selector

The "Cambridge Materials Selector" (CMS), produced by Granta Design Ltd. (UK), is a software tool for materials and process selection with databases covering about 2800 materials, 125 manufacturing processes and some 1900 shapes.

Unlike many other data bases, CMS contains values for *all* properties in *all* data sets. In order to keep this uniformity in documentation, estimates have at some points been made by the authors and are indicated as such in the data sets. This refers also to many energy entries.

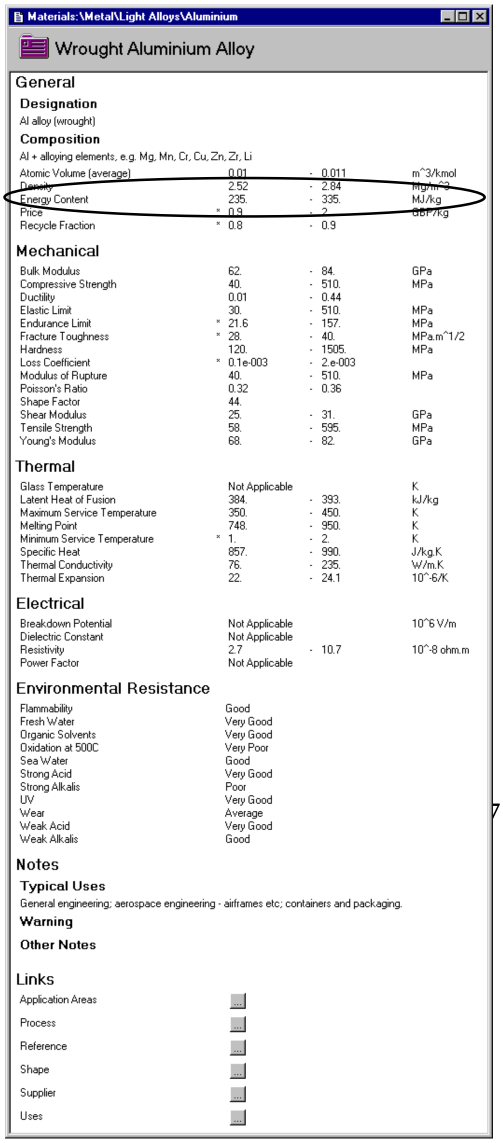
Although the primary goal of CMS is to support designers in the selection process by providing electrical, thermal and especially mechanical property data to be used in a unique selection method (see sec. 4.3.2), the tool also provides energy data on *each* material.

The energy entry of the exemplary material data sheet for "wrought aluminium alloy" is indicated on **figure 6.6** overleaf.

Description of the data:

- Fuel and feedstock share of materials data are *not* separated
- Energy data represent the sum of fuel and feedstock from cradle to gate, i.e. the total energy content

Figure 6.6 A typical CMS data set for a material, the energy content entry is encircled



Wrought Aluminium Alloy

General

Designation

Al alloy (wrought)

Composition

Al + alloying elements, e.g. Mg, Mn, Cr, Cu, Zn, Zr, Li

Atomic Volume (average)		0.01	-	0.011	m^3/kmol
Density		2.52	-	2.84	Mg/m^3
Energy Content		235.	-	335.	MJ/kg
Price	*	0.9	-	2	GBP/kg
Recycle Fraction	*	0.8	-	0.9	

Mechanical

Bulk Modulus		62.	-	84.	GPa
Compressive Strength		40.	-	510.	MPa
Ductility		0.01	-	0.44	
Elastic Limit		30.	-	510.	MPa
Endurance Limit	*	21.6	-	157.	MPa
Fracture Toughness	*	28.	-	40.	MPa.m^1/2
Hardness		120.	-	1505.	MPa
Loss Coefficient	*	0.1e-003	-	2.e-003	
Modulus of Rupture		40.	-	510.	MPa
Poisson's Ratio		0.32	-	0.36	
Shape Factor		44.			
Shear Modulus		25.	-	31.	GPa
Tensile Strength		58.	-	595.	MPa
Young's Modulus		68.	-	82.	GPa

Thermal

Glass Temperature		Not Applicable			K
Latent Heat of Fusion		384.	-	393.	kJ/kg
Maximum Service Temperature		350.	-	450.	K
Melting Point		748.	-	950.	K
Minimum Service Temperature	*	1.	-	2.	K
Specific Heat		857.	-	990.	J/kg.K
Thermal Conductivity		76.	-	235.	W/m.K
Thermal Expansion		22.	-	24.1	10^-6/K

Electrical

Breakdown Potential		Not Applicable			10^6 V/m
Dielectric Constant		Not Applicable			
Resistivity		2.7	-	10.7	10^-8 ohm.m
Power Factor		Not Applicable			

Environmental Resistance

Flammability	Good
Fresh Water	Very Good
Organic Solvents	Very Good
Oxidation at 500C	Very Poor
Sea Water	Good
Strong Acid	Very Good
Strong Alkalis	Poor
UV	Very Good
Wear	Average
Weak Acid	Very Good
Weak Alkalis	Good

Notes

Typical Uses

General engineering; aerospace engineering - airframes etc; containers and packaging.

Warning

Other Notes

Links

Energy data for manufacturing processes are not given.

Source 6:	**CMS [CMS 97]**
Age	Before 1997, updated data available
Specificity	The data are given as ranges for very specific materials
Way of collection	From literature and databases (*)

Data for Oil Point indicators were extracted from the generic database v 2.52 of December 1997.

(*) In its latest version, which due to its enlarged versatility is called “Cambridge Engineering Selector (CES)”, this software can directly exchange data with the Boustead Model 4 (see previous section).

7 EDIP LCA-tool

This database is related to an LCA-tool, which was developed over a period of five years in the course of the EDIP programme at the Insitute for Product Development, Technical University of Denmark. The tool supports the EDIP LCA method (see Chapter 3) and can be adapted to other methods.

The database comprises about 750 data sets on life cycle processes including auxiliary materials and energy systems, amoung these some 80 materials and 40 manufacturing processes. In the present research, version 2.11 (beta) of the tool of May 1998 was used.

Data in the EDIP tool are for professional LCAs and are, therefore, very detailed but at the same time transparent and well-documented. The computer tool supports the visualisation of data in many forms. By making a calculation of “Impact Potentials” (Characterisation phase of an LCA), fuel and feedstock energy requirements can be seperated for any system analysed.

Description of the data:

- Fuel and feedstock share of materials data are separated
- Materials data represent cradle-to-gate requirements

Resources, materials, auxiliary materials, related manufacturing processes, disposal processes and energy systems

Source 7:	**EDIP LCA tool [EDIP 98]**
Age	1992 to 1997, updated
Specificity	The manufacturing data are collected for very specific operations, materials data and other data are often averages
Way of collection	Data were measured at manufacturing companies by specialists, as well as retrieved from literature and branch organisations

6.11.8 IdeMat 98

IdeMat 98 is a software tool for environmental materials selection developed at the Faculty of Industrial Design, Delft University of Technology, The Netherlands. IdeMat provides a database with information on ca. 400 materials, about 40 manufacturing processes and some 60 other life cycle processes. Five components (two types of batteries and three metal tubes) are also included.

The database contains energy data for about half of the materials, a quarter of the manufacturing processes and for all (just under 20) transport processes. Energy data are given as GER values (Gross Energy Requirement). The GER or "total production energy" is *"the energy associated with* all *of the operations needed to support the production of a commodity or the provision of a service"*, [Boustead/Hancock 79], p. 15.

As a unique feature, the IdeMat database occasionally includes a flow chart of the processes included in a given data set. This visualises what the data comprise.

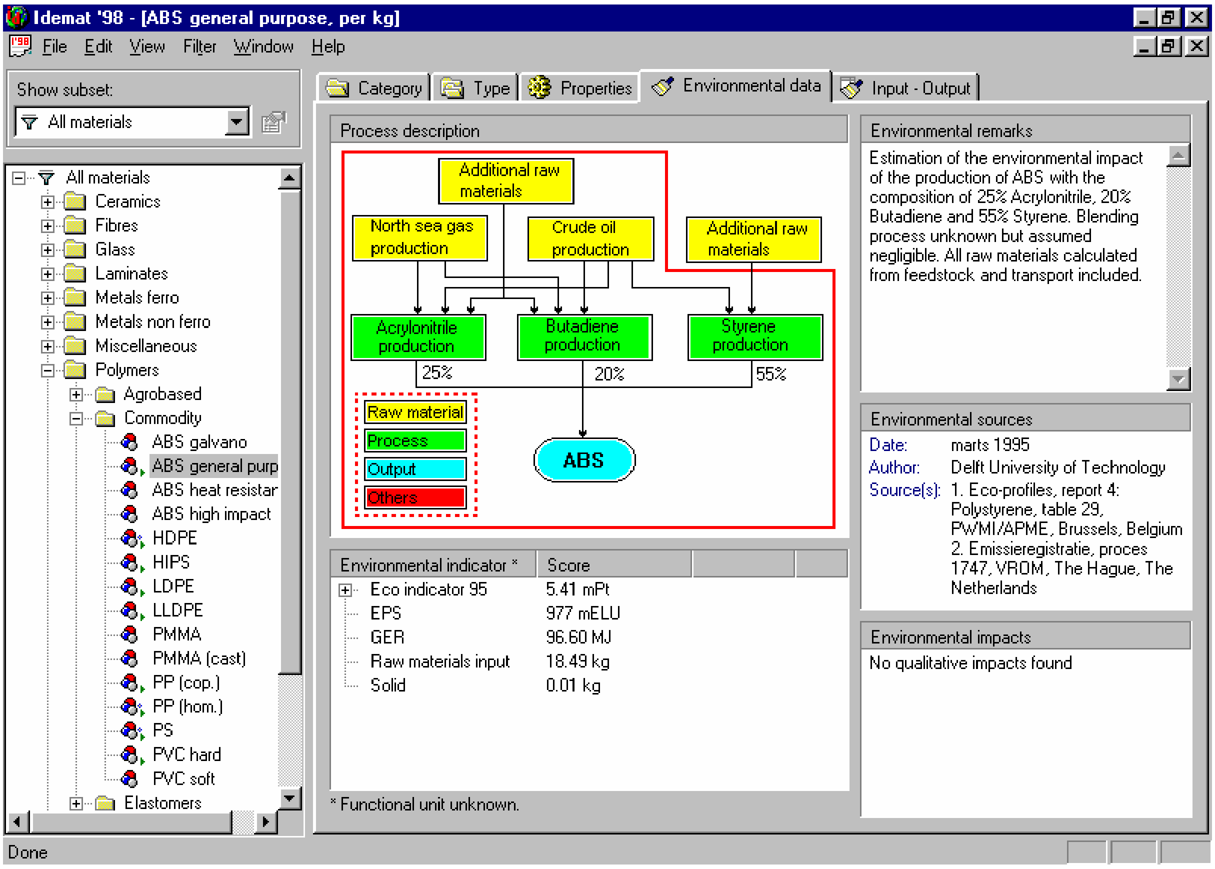
Description of the data:

- Fuel and feedstock share of materials data are *not* separated
- Materials data represent cradle-to-gate requirements

Materials, some manufacturing processes, disposal processes and transport processes

Source 8:	**IdeMat 98 tool [Idemat 98]**
Age	1995 to 1997
Specificity	The data are averages for specific operations
Way of collection	Mostly from literature

Figure 6.7 below shows an exemplary screen shot of the software. The GER value (Gross Energy Requirement) was used.



Estimation of the environmental impact of the production of ABS with the composition of 25% Acrylonitrile, 20% Butadiene and 55% Styrene. Blending process unknown but assumed negligible. All raw materials calculated from feedstock and transport included.

Environmental indicator *	Score
Eco indicator 95	5.41 mPt
EPS	977 mELU
GER	96.60 MJ
Raw materials input	18.49 kg
Solid	0.01 kg

* Functional unit unknown.

Date: marts 1995
Author: Delft University of Technology
Source(s): 1. Eco-profiles, report 4: Polystyrene, table 29, PWMI/APME, Brussels, Belgium
2. Emissieregistratie, proces 1747, VROM, The Hague, The Netherlands

No qualitative impacts found

Figure 6.7 Screen shot of IdeMat '98 data entry on "ABS, general purpose"

As can be seen on figure 6.7, IdeMat contains graphic models of the product system comprised by the data.

6.11.9 Summary

The data contents of all eight main sources utilised to derive Oil Point indicators is indicated in **table 6.10**. The brackets indicate that a source contains some data on a certain type of life cycle process, but that the number of data sets on this type is small.

"Use" stage data, for instance, are in all respective sources actually only represented by electricity or heat production processes. Concerning the "Boustead Model 4", only the manufacturing process data sets were extracted due to limited access to the software during the research. Data on materials and manufacturing processes, however, represent the major part of the data sets in this tool.

	Books, reports				**Software, databases**			
	Allen/Alting 86	APME Eco-profiles	Boustead/ Hancock 79	BUWAL no. 250 I & II	Cambridge Materials Selector	Boustead Model 4	EDIP LCA-tool	IdeMat 98
Originally collected data		X	X	X		X	X	
Materials		X	X	X	X	(X)	X	X
Manufacturing	X	X	X	X		X	X	X
Transport				(X)		(X)	X	X
Use				(X)		(X)	(X)	(X)
End-of- life				(X)		(X)	X	X

Table 6.11 Energy data in the used sources, divided into life cycle stages

It can be stated that only a few of these sources obtained data by original measurements or by collection at operating companies. These are Boustead (i.e. APME, Boustead/Hancock 79 and Model 4), BUWAL and EDIP. In general, the described data sources are considered to be "as good as it can get" in the field.

As stated earlier, MI-values from the MIPS method and values of the "Cumulated Energy Demand (CED, in German: KEA, see chapter 5)" have been taken into account at some points. Despite their relevance, CED values were only used to a limited extent because a publicly available database did not yet exist during this research.

Data on use and end-of-life processes were derived from additional sources, such as reports from producers, EPAs etc.

6.12 Derivation of Oil Point indicators and solving of related problems

Purpose with the collection of energy data had been to make the definition of a set of Oil Point indicators possible. It seemed most appropriate, to aggregate these indicators on "class"-level for processes regarding manufacturing, transport, use and end-of-life stage. For transport processes, for example, this meant to define only one OP indicator for respectively "truck transport", "air transport", "train transport" and the like, leaving out all members of a class such as "16t-truck transport", "5t-truck transport" etc.

For materials, however, the more detailed level of "type" was necessary (see section 6.7.1.). Obviously, one OP indicator for e.g. "metals" or for all "fibres" would not make sense.

The subsequent sections describe the way in which the Oil Point indicators were derived. One example is given for a “best case”, i.e. a case where similar data with a high quality were given from several sources. A “worst case” with only one source and low data quality is described as well. The complete list of resulting indicators is given in Appendix I.

6.12.1 A best case example

The ideal situation for the derivation of an OP indicator, e.g. for a certain material, would be to have several “good”, i.e. transparent, complete and reliable sources readily available, which state a similar energy value for that specific material. One could then be relatively sure that this value is realistic. In practice, however, such similarities between sources are rare.

PET resin for bottles

An exception are polymer data. Reason for similarities here is, that data on these materials often originate from the APME series of reports. For sources like BUWAL, EDIP, IdeMat, CMS and Boustead Model this is the case. Therefore, data for a polymer, e.g. “PET resin (bottle grade)” shall be discussed as a best case example.

The APME source gives the table below for the production of 1 kg PET resin (similar to table 6.8):

Fuel type	Fuel Production & Delivery Energy [MJ]	Energy content of delivered fuel [MJ]	Energy use in Transport [MJ]	Feedstock Energy [MJ]	Total Energy [MJ]
Electricity	5.56	2.50	0.03	< 0.01	8.10
Oil fuels	1.48	11.57	0.28	32.54	45.87
Other fuels	3.26	14.05	0.05	6.16	23.51
Total [MJ]	10.30	28.11	0.37	38.69	**77.47**

Table 6.12 Gross energy required to produce 1 kg of bottle grade PET (Totals may not agree because of rounding) [APME 99a], tab. 1, p. 4. The fuel part of the gross energy requirement is encircled.

Important values from this table are:

- 77.47 MJ/kg, the total energy requirement (also called total energy content) and
- 38.69 MJ/kg the feedstock share.

The total fuel energy required is the difference between those two values, i.e. 38.78 MJ/kg (This equals the sum of the encircled values in table 6.11).

Oil Point indicators (OPIs) for a material M can be calculated using equation 6.1:

$$OPI_{Material\ M} = \frac{Total\ energy\ content_{Material\ M}}{Energy\ content\ represented\ by\ one\ Oil\ Point} \tag{6.1}$$

The Oil Point indicator for PET resin can, thus, be determined by the following calculation:

$$\begin{aligned} OPI_{PET\ resin} &= \frac{Total\ energy\ requirement_{PET\ resin}}{Energy\ content\ represented\ by\ one\ Oil\ Point} \\ &= \frac{77.47\ MJ/kg}{45\ MJ/OP} \\ &= 1.722\ OP/kg \end{aligned} \tag{6.2}$$

Oil Point indicators are usually limited to one decimal figure in order to keep calculations simple. Thus, the Oil Point indicator for PET resin could be defined as follows:

$$Oil\ Point\ indicator_{PET\ resin} = 1.7\ OP/kg \tag{6.3}$$

However, PET - like all polymers and all naturally grown materials - is a fuel bearing material. In order to enable calculations in the stages Materials Production and End-of-life of a product made from this material, separated Oil Point indicators for fuel share and feedstock share have to be derived. This involves the following two calculations, again using the data from table 6.11:

$$\begin{aligned} OPI_{PET\ resin,\ fuel} &= \frac{Fuel\ energy\ requirement_{PET\ resin}}{Energy\ content\ represented\ by\ one\ Oil\ Point} \\ &= \frac{38.78\ MJ/kg}{45\ MJ/OP} \\ &= 0.862\ OP/kg \end{aligned} \tag{6.4}$$

$$\begin{aligned} OPI_{PET\ resin,\ feedstock} &= \frac{Feedstock\ energy_{PET\ resin}}{Energy\ content\ represented\ by\ one\ Oil\ Point} \\ &= \frac{38.69\ MJ/kg}{45\ MJ/OP} \\ &= 0.860\ OP/kg \end{aligned} \tag{6.5}$$

Rounding these values to one decimal results in a value of 0.9 OP/kg for both fuel share and feedstock share.

The sum of these two, however, is then 1.8 OP/kg, which is 0.1 OP/kg more than the OP indicator calculated in equations 6.2 respectively 6.3. (This is the same rounding problem named in the remark of table 6.11). As an exception from the rule, both indicators are, therefore, described with two decimals.

The Oil Point indicators for fuel share and feedstock share of PET resin (bottle grade) are thus:

$$OPI_{PET\ resin,\ fuel} = 0.85\ OP/kg \tag{6.6}$$

$$OPI_{PET\ resin,\ feedstock} = 0.85\ OP/kg \tag{6.7}$$

This *equal size of fuel and feedstock share* is not typical for polymers. For some polymers, the fuel share can be about two thirds of the total energy content (see Appendix I). In general, a value of about 1…2 OP/kg for either share can be considered typical for polymers.

6.12.2 A worst case example

A worst case could be to either only have unreliable data or no data at all for a certain life cycle process. This could, for instance, be the case for entirely novel materials or processes but is also often true for use processes.

In a first evaluation, it is appropriate to make a “worst case” estimate and then see – in a brief sensitivity check (step 3 a) – whether the this value has a relevance for the overall result or not. If not, no further data retrieval is needed.

If, however, the value turns out to be relevant for the overall result, there are three sensible things to do:

1. Derivation by comparing with existing Oil Point indicators
2. Retrieval of the missing value from readily available sources
3. Contacting a specialist

Estimation

As the first option, the missing value can be estimated by means of comparison with other values or based on experience. Practitioners in environmental evaluation usually rely in that case on their experience. (This practice is sometimes referred to as “educated guessing” or “guess-timation”). To give designers this possibility too, has been a very important reason for the development of the OPM in the first place. It is, therefore, considered a substantial advantage of the OPM towards other indicator-based methods. It is assumed that this can also be carried out by designers after some training.

A plastic material, for instance, is very likely to have a total energy requirement of about 2 Oil Points per kilogram because the range of the materials mentioned in the Appendix I is between 1.5 and 3.0 OP/kg. Metal removing processes require about 2 MJ per kilogram of removed material (see Appendix *"Review of energy consumption of manufacturing processes"*) and plastic processing requires roughly 10 MJ/kg [Boustead 97, Ashby 98]. Energy data of use processes, finally, may well be estimated based on knowledge of behaviour in the designer's own household. It is strongly assumed that, based on such information and on the list of OP indicators given in Appendix I, a derivation of a missing indicator is possible, even for designers. Here, the fact that designers are familiar with energy as such is an advantage.

Retrieval from readily available sources

The second option is to derive energy values from readily available sources, such as the Internet, data bases, books, etc. Some sources for energy data retrieval are given in Appendix I. The general advantage of the OPM being based on energy data here is, that energy consumption data are actually available from many sources - as opposed to, for instance, emission data of a certain process.

The third option, i.e. contacting a specialist, is especially relevant for designers in companies, where an environmental specialist might be employed. In general, an external specialist could be contacted as well. However, as the OPM is meant to be used in conceptual, brainstorming-like working environments, this last option is more of theoretical than practical character.

Recent data

There are different sources for this material, namely older and more recent reports from APME. Due to the technological improvements in processing industry, it was tried to use the most recent data for the definition of Oil Point indicators. In practice, however, a missing indicator could also be derived based on data, which are older but at hand.

6.12.3 Handling ranges and averages

For a sensitivity analysis it is important to know, whether an average was built from a relatively wide range of values or from a narrow one. In order to keep this transparency of the data, the range from which the average was built should always be mentioned. In the OPM, ranges of data used to derive Oil Point values are therefore mentioned as "narrow" or "wide".

Narrow ranges cover values between one and just under two times the Oil Point value (factor 1 to 1.99). Wide ranges cover values between 2 and 5 times the Oil Point value (factor 2 to 5). Ranges above factor five are mentioned as "extremely wide". They are often caused by exotic members of the respective group. In the stated "typical mean values", the influences of such exotic values are eliminated.

6.12.4 Factors and common obstacles to be aware of when handling energy data

A main intention with using energy relationships in the Oil Point Method is the fact that energy data, in general, are easier available than other inventory data in case they have to be retrieved.

However, before using energy data from literature, from the Internet or from other sources a few things should be checked. These are:

! What do the data cover?
All “cradle-to-gate” processes or maybe just extraction?
The total inherent energy in a material or just its processing?
(see figure 6.6. p. 127)

! How is electricity calculated?
By using the thermodynamical ideal of 3.6 MJ per kilowatt-hour or by including efficiency (and which factor)?
As a typical factor, about 33% efficiency can be assumed as average in Europe.

! Are overhead consumptions included in the data for manufacturing processes or not?
Overhead energy consumption may typically be between 50% and 75% of the total energy consumption in a factory of electromechanical products.

! Are the values derived by estimation, calculation or measurement?
If so, how has this been done?

! What technological standard was used?
Energy data come from technical processes, which are subject to change over time. Technology gets more efficient and thus the fuel part (processing part) of the energy content may be reduced.
Energy data collected recently and /or referring to state-of-the-art technology are thus usually lower in value than data from older sources (in the order of some percent).

The ultimate basis for the data are physical laws. On a higher level of abstraction, the basis can be established well-documented data bases. Both of these ways were chosen in this research.

6.13 Characteristics of the OPM

In summary, the Oil Point Method has the following characteristics:

- The OPM is a quantitative method for environmental, life cycle-wide evaluations and comparisons of material and process alternatives.

- The Oil Point method is exclusively based on energy considerations and does not take toxicological aspects into account. This means that its application is limited to certain groups of products where energy aspects are pre-dominant.

- Despite the consideration of energy requirements, the OPM is no Life Cycle Energy Analysis as such as it does not have energy requirements as such in focus of interest but rather environmental impact related to energy production. Primary energy is only used as a unit to quantify related impacts.

- The OPM has a ‘low resolution’, i.e. it does not reflect details - neither with respect to the product (e.g. the precise weight of a product component is not needed) nor with respect to the result (e.g. not the whole environmental impact is quantified). Oil Point evaluations produce rough indicative results. These are, however, sufficient and appropriate for early product development.

- The OPM is meant to be used on a routine basis by individuals without specific knowledge in environmental evaluation.

- Candidate materials with environmentally superior characteristics than a given one are not suggested by the method. They have to be sought by the designer who can evaluate them subsequently.

- Estimations of indicators are explicitly allowed in the method, especially as first iterations.

7 Case Studies and Validation of the Method

In the previous chapter, a method to support rough environmental decision-making was suggested, and the application of the method was explained both in general terms and by means of a case study.

This chapter has the aim to validate the method, understood as the "examination of the method with respect to certain aspects in order to declare it for valid". This is done by means of five case studies.

7.1 Aspects to examine

Based on the overall aim of this project, there are three aspects to examine in the course of validating the OPM:

1. *Accordance of results*

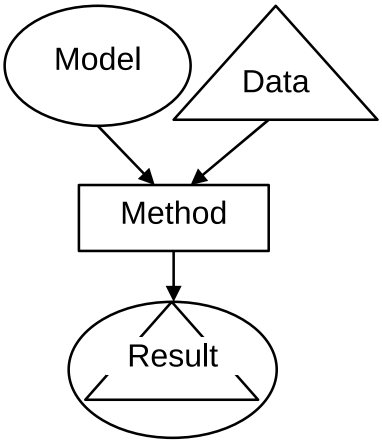
   Does the method deliver results, which - on the overall basis - are in accordance with results from other quantitative methods, ultimately from a formal LCA?

2. *Applicability*

   Is the method applicable by designers in their daily work?

3. *Application area*

   Bearing in mind the omission of chemical aspects, in which areas, e.g. certain product groups, industrial branches or service sectors, is it sensible to use the method and in which not?



A result of an environmental evaluation is always dependant on the way the actual life cycle is *modelled* and on the *data* used in this model. In any method, model and data are used to produce a result. The model always incorporates assumptions, just as data always incorporate uncertainties.

In order to test methods against each other, both model and data thus have to be the same in each test. In the case studies presented in this chapter, it was therefore tried as much as possible to use the exact same data and the same model of the respective life cycle; otherwise, this is stated.

Applicability

Applicability of the Oil Point Method is considered to be ensured by the utilisation of indicators in the method. Its principle of calculating with specific quantities (i.e. indicators) is well-known also by industrial designers e.g. from prices given per kilogram of material. A number of seminars with designers, LCA experts and researchers held for the reason of discussing tools and methods for environmental product design did not refute this expectation. Learning how to use and apply the Oil Point Method is therefore not considered to be a problem.

Application area

The aspects “Accordance of results” and “Application area” are interrelated: Those cases where the OPM leads to substantially different results than a formal LCA obviously belong to an area where the method cannot be applied meaningfully. As the OPM is related to energy requirements, *“energy consumption”* is chosen as the criterion for distinction of application areas.

Thus, the validation of the method is performed for three major types of products or services:

- “directly energy consuming” or: active,
- “not energy consuming” or: passive and
- “indirectly energy consuming” or: hybrid.

Active products

Basis for assigning a product or service to one of the groups “active”, “passive” and “hybrid” is the fulfilment of the primary function of the product: If any form of energy other than muscle power of the user is necessary to fulfil the primary function of the product, it belongs to the group of active products.

Typical representatives of this group are, for instance, all electricity- or liquid fuel-driven products: A TV-set does only display broadcast programmes, if electric energy is supplied. A car does only transport passengers and/or loads, if fuel is supplied to the engine.

Passive products

If no energy (other than muscle power) is required to fulfil the primary function of the product, it belongs to the group of passive products. Furniture and buildings are good examples for this group of products.

Hybrid products

Products, which do not require energy to fulfil their primary function but which do so to *maintain* the primary function are classified as hybrid. Such products are, for instance, textiles and garments. They don’t require energy for wearing them but for the (usually) inevitable washing processes maybe succeeded by tumble-drying. Cutlery and pottery also belong to the group of hybrid products.

The main aspect in support of application is the fact that whenever a certain OP-indicator should be missing, e.g. because a more detailed evaluation is desired, this indicator can be defined by the designer him- or herself.

The basic rules for defining Oil Point indicators are mentioned in chapter 6. Sources for energy data, including Internet links, are given in Appendix II.

Accordance of results

The validation with respect to the accordance of results is in each case based on the same data and assumptions and is done by comparing the results of Oil Point evaluations with results of two other established quantitative methods for environmental assessment in product design: the Eco-indicator 95 method [Goedkoop 95a] and the EDIP method [Wenzel et al. 97].

7.2 The methods used

The methods used to cross-check the OPM have been explained in detail in chapter 5. They are therefore only described in brief at this place.

EDIP method

EDIP (Environmental Design of Industrial Products) is a formal LCA method, which accounts resource consumptions, environmental, impacts and impacts on the working environment separately.

Results are calculated and presented in a non-aggregated form in order to maintain transparency. For the comparisons with other methods, only the environmental results were used, neglecting both resource consumption and working environment. The EDIP-calculations were made by means of the LCV-tool, which includes a database with some 750 unit processes and exchanges.

In order to facilitate a comparison with the single score results of the other two methods, the non-aggregated weighted environmental contributions were summed-up to a single figure. (The aggregation is not part of the method.) This result obtained using the EDIP method is taken as ultimate reference in each case study.

Eco-indicator 95

In contrast to that, the Eco-indicator 95 (EI 95) method is a typical example for a simplified LCA method. Potential environmental damage related to a unit quantity of e.g. material is here aggregated to a single figure, the Eco-indicator. Calculations are done using such indicators and the result is a single score.

Primary source of Eco-indicators used for the case studies was the “Manual for Designers” [Goedkoop 95b]. A few Eco-indicators, not found there, were taken from the Idemat tool [Idemat 98].

A comparison of EDIP results and Eco-indicator 95 results with results obtained by using the OPM should then reveal, whether or not application of the OPM leads to similar overall results - in spite of the simplifications made in the OPM including the disregard of chemical aspects.

"Similar overall results" could either be the identification of the same material as environmentally preferable for a given application (in a comparative study) or the identification of the same life cycle stage(s) as the problematic one(s).

7.3 Selection of cases

The OPM is developed to support environmental materials and process selection in the early stages of product design including conceptual and embodiment design. Within this scope, it is meant to assist in the rough investigation of the environmental performance of members of different materials classes such as wood, plastic, steel etc. This means that the method is not well-suited for detailed analyses such as, for instance, the comparison of different types of mild steel for a given application.

The relation of the method to industrial products as such and to associated services is based on the application, namely to support materials and process selection. Therefore, the method is not well-suited for environmental decision-making on other than industrial products, e.g. in the agricultural sector. These constraints are taken into account in the case studies.

The case studies comprise examples for all three major types of products defined earlier, i.e. active, passive and hybrid:

1. A coffee machine
2. A vacuum cleaner
3. Two window frames
4. A chair
5. Two sweaters

A coffee machine and a vacuum cleaner

As "active" products, a coffee machine and a vacuum cleaner are analysed. The coffee machine case is conducted in order to illustrate the dominant role energy consumption today typically has for the overall environmental effect of intensively used active products. Case 2, the vacuum cleaner, in turn, is also an active product but is only used sporadically.

Two window frames and a chair

"Passive" products are represented by case studies on two window frames and on a chair. The window frame case is a comparison between two materials. (The OPM evaluation of this case had been used earlier to explain the method itself.) A difference between the two cases can be seen in the fact that window frames are influenced by weather conditions, resulting in wear and shortened life time, while furniture is not.

Two sweaters

From the group of "hybrid" products, two sweaters are evaluated. A natural material is compared to a synthetic one.

It was decided not to consider overhead energy during manufacturing in any of the cases.

Analytical cases vs. comparative cases

Materials and process selection is, per se, a comparative process. The comparison of the environmental performance of different solutions, in turn, comprises the analysis of each solution (or, at least, the analysis of one solution and the substitution of certain elements in this analysis by elements of the other solution(s)). This means that, if two methods come to similar results in an analysis, they will also come to similar results in a comparison. For the comparison of results of the different methods – and thus for the validation of the OPM - it is therefore sufficient to make analyses even though primary application area are comparisons.

Comparative cases for passive and hybrid products

Three of the five case studies are therefore analytical ones while only two are comparative ones. These comparative cases are conducted in those areas, where the influence of materials selection is supposed to be significant, namely for passive and hybrid products.

The outcome of the cases on the window frames, the chair and the sweaters is also of particular interest because here the disregard of chemical aspects in the OPM is expected to lead to deviating overall results in the three methods.

The case studies follow a common structure, which reflects the three basic steps in the OPM:

1. A short description of the product(s) including an exemplary picture and the definition of a Functional Unit
2. One respectively all three evaluations and
3. A summarised result with brief conclusions.

A flow chart model of the life cycle (i.e. the product system) is sometimes included as well. An overview over the cases and the methods used is given in **table 7.1**.

Product type		**Case**	**Method**		
	Aspect of interest		EDIP	Eco-indicator 95	OPM
Active	Intensive use	1. Coffee machine	**X**	**X**	**X**
	Sporadic use	2. Vacuum cleaner	**X**		**X**
Passive	Material comparison	3. Window frames	**X**	**X**	**X**
	Long life time	4. A chair	**X**		**X**
Hybrid	Material comparison	5. Sweaters	**X**		**X**

Table 7.1 Overview over case studies and used methods

7.4 Case 1: A coffee machine

In this case study, a regular coffee machine is analysed. Aim is not only to investigate improvement potentials but especially to study correlations between the results obtained and conclusions to be drawn by using the different methods for evaluation.

7.4.1 Product system and Functional Unit of the coffee machine

Figure 7.1 depicts the product system of a coffee machine. The example is taken from the “Eco-indicator 95 Manual for designers” [Goedkoop 95b].

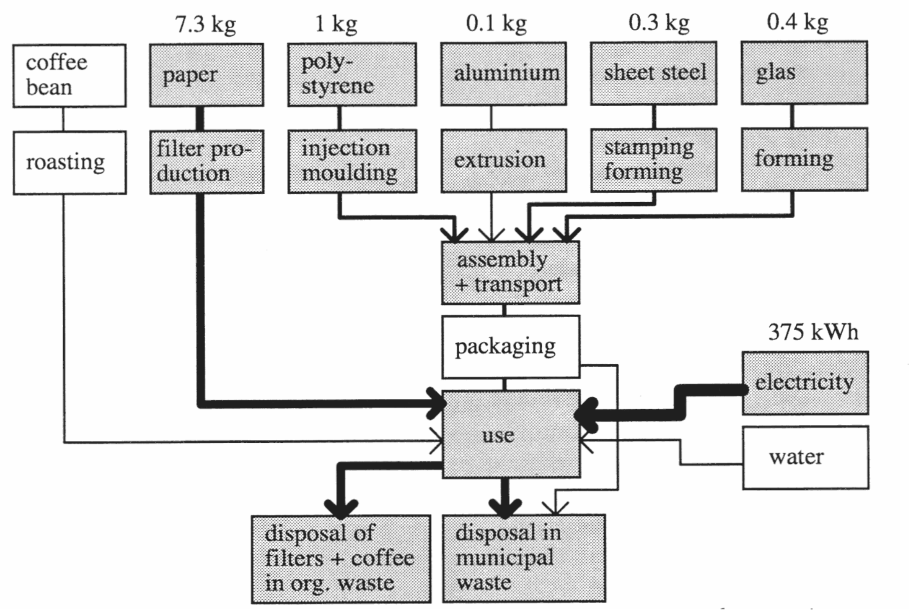


Figure 7.2 The product system of a coffee machine [Goedkoop 95b]

The model and data given there have been used for the EDIP evaluation (done by means of the LCV-tool) and for the Oil Point evaluation. This means that all three evaluations are based on the same data.

The coffee machine consists of a polystyrene housing, a glass jug, a steel hot plate and an aluminium riser pipe. Cables, switches and packaging are omitted as well as the coffee beans and the consumed water (see the white building blocks in figure 7.1).

Functional Unit

The Functional Unit (i.e. the service to be delivered) is defined as *“brewing of coffee in a regular coffee machine over a period of five years with two daily uses where one use includes a brewing of 6 cups (i.e. half capacity) and a period of 30 minutes of keeping the coffee hot, all taking place in Europe”*.

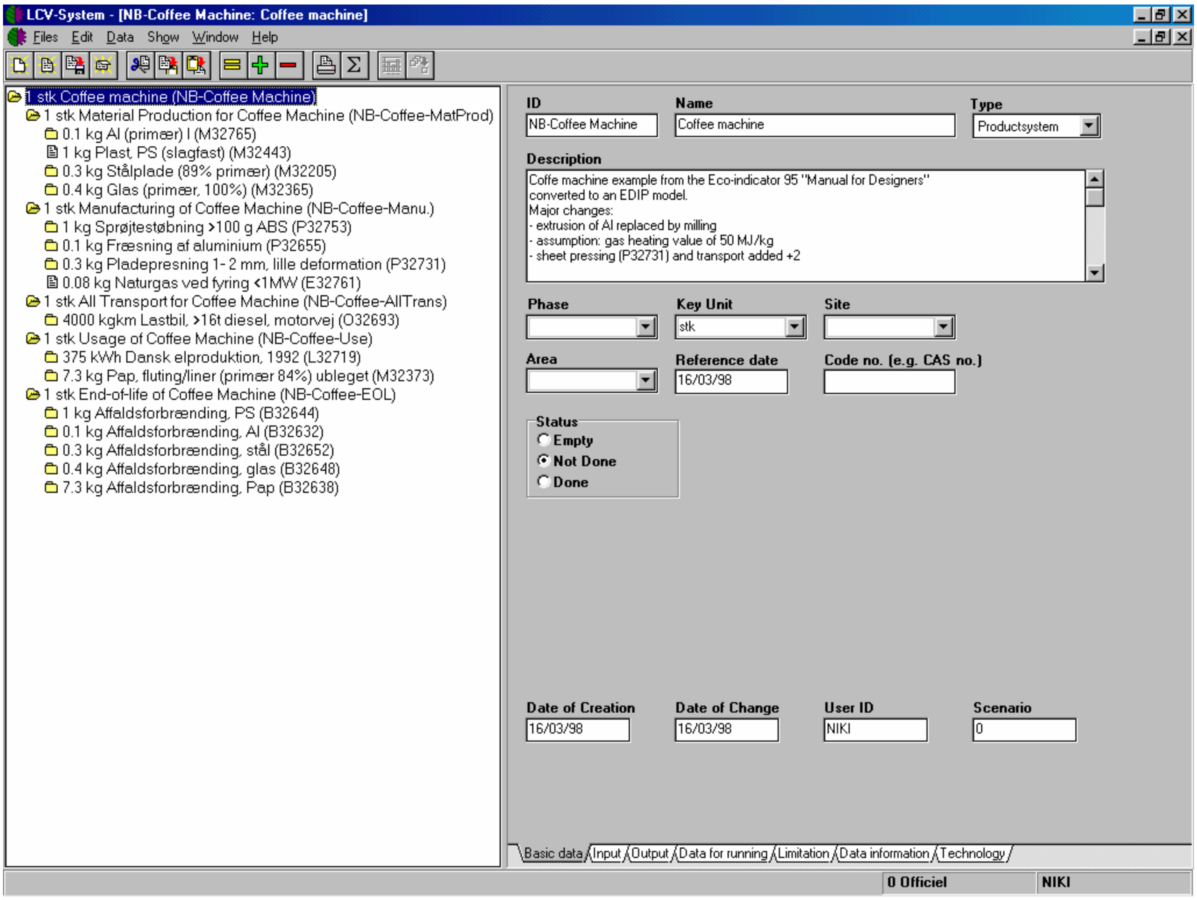
Some Inventory data are also given in figure 7.1. Relative size of flows is indicated by the thickness of the arrows. Due to the lack of transport data in the example of [Goedkoop 95b], a transport scenario within Europe is added.

The disposal scenario is “incineration” due to the assumed disposal in municipal waste in Europe. Added transport scenario and calculation of electricity consumption are given below.

- 4 tkm truck transport: from an assumption of 4 kg product incl. packaging transported over a distance of 1000 km by truck
- 375 kWh electricity: from 5 years life time, 2 brewings per day at half capacity incl. 30 min on hot plate, about 0.1 kWh per brewing; based on measurements by [Goedkoop 95b]

7.4.2 EDIP, EI 95 and OPM evaluations

Based on these data, the three evaluations of the coffee machine were carried out. The EDIP result was calculated by means of the LCV tool.



- 1 stk Coffee machine (NB-Coffee Machine)
  - 1 stk Material Production for Coffee Machine (NB-Coffee-MatProd)
    - 0.1 kg Al (primær) I (M32765)
    - 1 kg Plast, PS (slagfast) (M32443)
    - 0.3 kg Stålplade (89% primær) (M32205)
    - 0.4 kg Glas (primær, 100%) (M32365)
  - 1 stk Manufacturing of Coffee Machine (NB-Coffee-Manu.)
    - 1 kg Sprøjtestøbning >100 g ABS (P32753)
    - 0.1 kg Fræsning af aluminium (P32655)
    - 0.3 kg Pladepresning 1- 2 mm, lille deformation (P32731)
    - 0.08 kg Naturgas ved fyring <1MW (E32761)
  - 1 stk All Transport for Coffee Machine (NB-Coffee-AllTrans)
    - 4000 kgkm Lastbil, >16t diesel, motorvej (O32693)
  - 1 stk Usage of Coffee Machine (NB-Coffee-Use)
    - 375 kWh Dansk elproduktion, 1992 (L32719)
    - 7.3 kg Pap, fluting/liner (primær 84%) ubleget (M32373)
  - 1 stk End-of-life of Coffee Machine (NB-Coffee-EOL)
    - 1 kg Affaldsforbrænding, PS (B32644)
    - 0.1 kg Affaldsforbrænding, Al (B32632)
    - 0.3 kg Affaldsforbrænding, stål (B32652)
    - 0.4 kg Affaldsforbrænding, glas (B32648)
    - 7.3 kg Affaldsforbrænding, Pap (B32638)

ID: NB-Coffee Machine
Name: Coffee machine
Type: Productsystem

Description:
Coffe machine example from the Eco-indicator 95 "Manual for Designers"
converted to an EDIP model.
Major changes:
- extrusion of Al replaced by milling
- assumption: gas heating value of 50 MJ/kg
- sheet pressing (P32731) and transport added +2

Phase:
Key Unit: stk
Site:
Area:
Reference date: 16/03/98
Code no. (e.g. CAS no.):

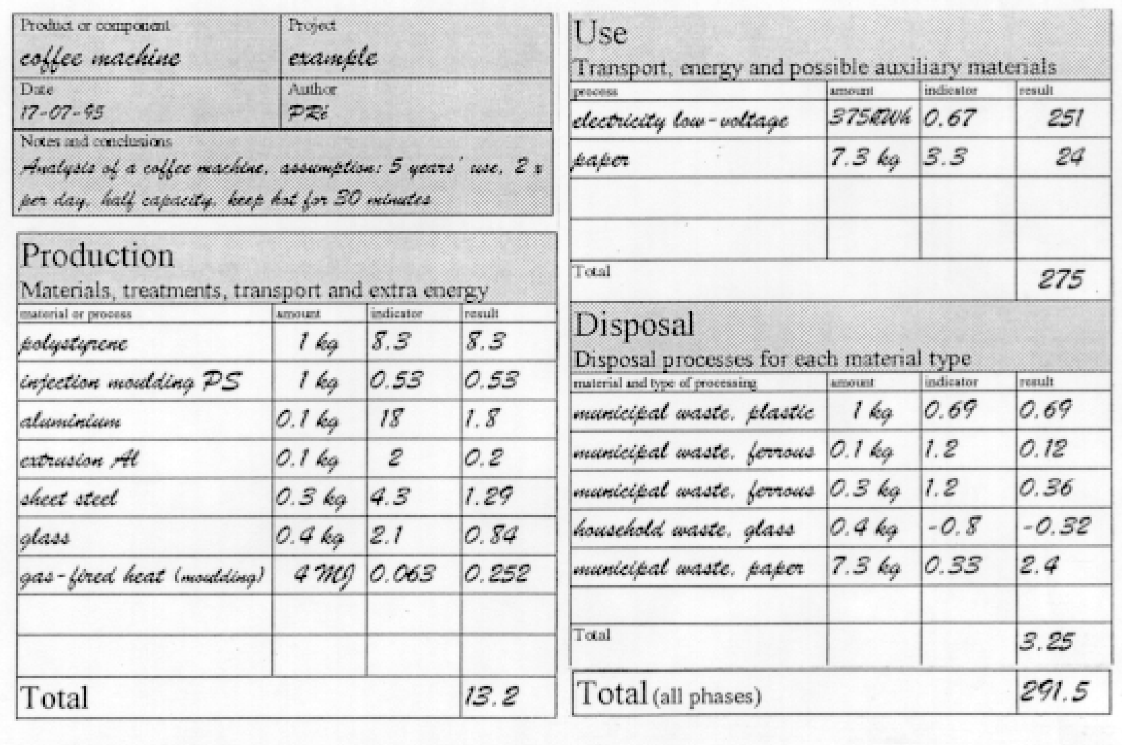
Status
○ Empty
● Not Done
○ Done

Date of Creation: 16/03/98
Date of Change: 16/03/98
User ID: NIKI
Scenario: 0

0 Officiel
NIKI

Figure 7.2 The product system of the coffee machine as modelled in the EDIP LCV-tool [EDIP 98]

A screenshot of the product system is shown in **figure 7.2**. The derivation of results in the EDIP method is described in detail in case 3 on window frames (section 7.6). The related summations of EDIP results - which are not part of the original EDIP method - will be explained there.



Product or component	Project
coffee machine	example
Date	Author
17-07-95	PRé

Notes and conclusions
Analysis of a coffee machine, assumption: 5 years' use, 2 x per day, half capacity, keep hot for 30 minutes

Production
Materials, treatments, transport and extra energy

material or process	amount	indicator	result
polystyrene	1 kg	8.3	8.3
injection moulding PS	1 kg	0.53	0.53
aluminium	0.1 kg	18	1.8
extrusion Al	0.1 kg	2	0.2
sheet steel	0.3 kg	4.3	1.29
glass	0.4 kg	2.1	0.84
gas-fired heat (moulding)	4 MJ	0.063	0.252
Total			13.2

Use
Transport, energy and possible auxiliary materials

process	amount	indicator	result
electricity low-voltage	375kWh	0.67	251
paper	7.3 kg	3.3	24
Total			275

Disposal
Disposal processes for each material type

material and type of processing	amount	indicator	result
municipal waste, plastic	1 kg	0.69	0.69
municipal waste, ferrous	0.1 kg	1.2	0.12
municipal waste, ferrous	0.3 kg	1.2	0.36
household waste, glass	0.4 kg	-0.8	-0.32
municipal waste, paper	7.3 kg	0.33	2.4
Total			3.25

Total (all phases)	291.5

Figure 7.3 Evaluation of the coffee machine by means of the Eco-indicator 95 [Goedkoop 95b]

The model and data given there have been used for the EDIP evaluation (done by means of the LCV-tool) and for the Oil Point evaluation. This means that all three evaluations are based on the same data.

The Eco-indicator 95 evaluation is shown below as a copy from [Goedkoop 95b]. The source mentions an Eco-indicator of 0.34 mp per ton kilometre (28 t truck at 60 % loading) as European average. For the transport scenario of 4 tkm (ton kilometres), this results in additional 1.36 mp for transport.

The Oil Point evaluation is shown by means of the table on the next page.

Life cycle stage	Material or Process	Quantity	OP indicator	Result
Material Production	Polystyrene (PS)	1 kg	2.1 OP/kg	2.1 OP
	Aluminium (primary)	0.1 kg	5.1 OP/kg	0.5 OP
	Sheet steel	0.3 kg	0.4 OP/kg	0.1 OP
	Glass (formed)	0.4 kg	0.3 OP/kg	0.1 OP
	Sub total:	**1.8 kg**		**2.8 OP**
Manufacturing	Injection moulding	1 kg	0.4 OP/kg	0.4 OP
	Extruding (aluminium)	0.1 kg	0.2 OP/kg	> 0 OP
	Sheet pressing	0.3 kg	0.1 OP/kg	> 0 OP
			Sub total:	**0.4 OP**
All Transport	truck transport	4 tkm	10 OP/1000 tkm	≈ 0 OP
			Sub total:	**0 OP**
Use	Electricity	375 kWh	0.25 OP/kWh	93.8 OP
	Paper filters	7.3 kg	0.9 OP/kg	6.6 OP
			Sub total:	**100.4 OP**
End-of-Life	PS incineration	1 kg	1 OP/kg	1 OP
	Aluminium incineration	0.1 kg	0 OP/kg	0 OP
	Sheet steel incineration	0.3 kg	0 OP/ kg	0 OP
	Glass incineration	0.4 kg	0 OP/kg	0 OP
	Paper incineration	7.3 kg	0.9 OP/kg	6.6 OP
			Sub total:	**7.6 OP**
			TOTAL:	**111.3 OP**

Table 7.2 Evaluation of a coffee machine using the Oil Point method

7.4.3 Summarised result and conclusions

Table 7.3 summarises the evaluation results for the coffee machine.

	Coffee Machine		
	EDIP [mPET]	Eco-indicator 95 [mp]	OPM [OP]
Material Production	1.2	12.2	2.8
Manufacturing	0.2	1.0	0.4
All Transport	0.0	1.4	0.0
Use	37.4	275	100.4
End-of-life	1.0	3.3	7.6
Totals:	**39.8**	**292.9**	**111.3**

Table 7.3 Results of the coffee machine case

All three evaluations exhibit the Use stage as the one with the by far highest potential environmental impact in the coffee machine's life cycle - in all evaluations more than 90 % of the total score. Also, Manufacturing and Transport are irrelevant for the result of all three methods.

Material production is more important for the overall result than the End-of-life stage in (the modified) EDIP and EI 95. In the OPM, this is vice versa (see table 7.2). While in OPM and EI 95 both Material production and End-of-life have a minor share of the overall result, they have a bigger share in the EDIP result.

These results are also shown on the bar chart diagram on the left (**fig. 7.4**).

The major design conclusion to be drawn from these results is to reduce impacts originating from the Use stage of the coffee machine. In all three methods, more than 90 % of this impact from the Use stage are related to electricity consumption, the rest to the filter paper.

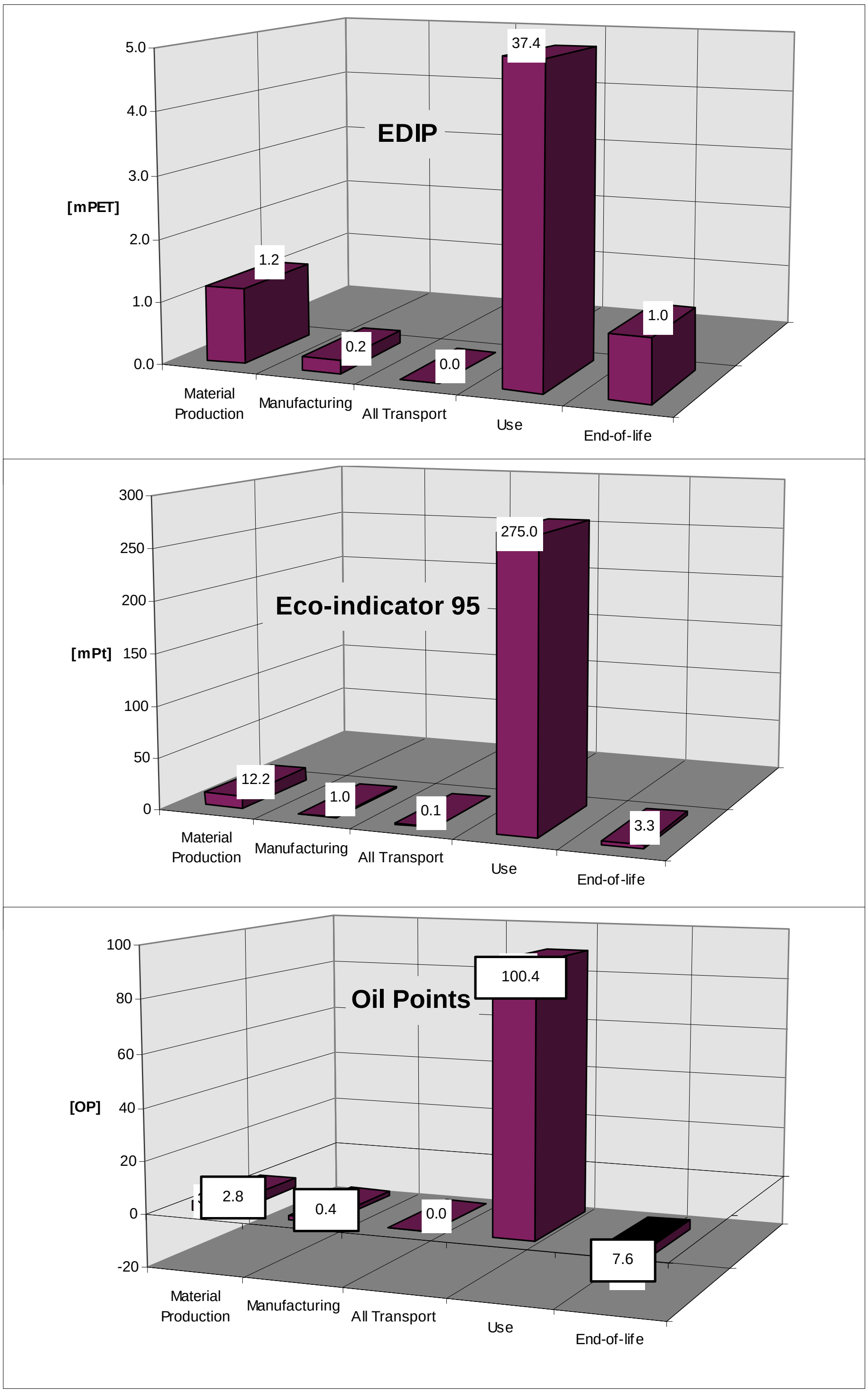


Figure 7.4 Bar chart results of the coffee machine case

For the designer, this means primarily to explore options, which reduce electricity consumption. A thermos-jug instead of the glass jug could be investigated as an alternative solution to be checked by another evaluation.

Replacing the paper filters by a permanent (e.g. metal) filter is the second best option according to all methods – still more important than using another material for the housing or to design the coffee machine for improved disassemblability and recycling.

It is important to notice that all these conclusions can already be drawn from the Oil Point evaluation alone.

On the overall level, a correlation between the three methods is evident in this case study as all product design-related conclusions can be drawn from each of them. For rough evaluations of intensively used active products the energy-based Oil Point Method can thus be declared for valid.

7.5 Case 2: A vacuum cleaner

The subject of this case study is a standard "pull behind" vacuum cleaner. It will only be analysed by means of the OPM because main interest is this time to determine, whether electricity consumption of an only sporadically used active product exhibits the same dominance in relation to e.g. materials selected as it was the case for intensively used ones, as seen in the case study before.

7.5.1 Product system and Functional Unit

The product system of the vacuum cleaner comprises various materials: including 0.5 kg primary cast aluminium as structural component, a chromium-plated steel tube of 2 kg, 3kg injection moulded polypropylene, an electric motor of 1000 W effect and 1 kg cardboard for packaging. The total weight including packaging is about 10 kg.

The product system also involves 3 ton-kilometres of truck transport and an estimated use stage of 15 years with weekly uses for 1 hour at full power. 98 paper sacks of about 50 grams each are included as well. The end-of-life scenario is incineration and the whole life cycle takes place within Europe.

The Functional Unit is defined as follows: "*Vacuum cleaning of about 100 m^2 wood and carpet floor for 1 hour once a week over 15 years in a European household*".

7.5.2 OPM Evaluation

The complete OPM calculation of the vacuum cleaner is given in the table below (Data from [Hermannsen 99]).

Life cycle stage	Material or Process	Quantity	OP indicator	Result [OP]
Material	Aluminium (cast, primary)	0.5 kg	6 OP/kg	3
Production	steel tube (low alloy)	2 kg	2 OP/kg	4
	Polypropylene (PP)	3 kg	2 OP/kg	6
	POM (as ABS)	0.1 kg	2.5 OP/kg	0.3
	Polyamide (PA)	0.3 kg	3.5 OP/kg	1
	ABS (high impact)	0.6 kg	2.5 OP/kg	1.5
	1 kg electric motor (1000 W) (50% St, 50% Cu):			
	copper	0.5 kg	3.1 OP/kg	1.6
	steel	0.5 kg	1.5 OP/kg	0.8
	Rubber (calculated as ABS)	0.3 kg	2.5 OP/kg	0.8
	textile sack (calculated as cotton)	0.5 kg	0.2	0.1
	card board	1 kg	1 OP/kg	1
	Sub total:	**9.3 kg**		**20.1**
Manufacturing	Aluminium, casting	0.5 kg	0.6 OP/kg	0.3
	steel tube, manufacturing	2 kg	0.6 OP/kg	1.2
	steel tube, chromium plating (calculated as 1 kWh)	187,500 mm^2	0.25 OP/kWh	0.25
	PP, injection moulding	3 kg	0.6 OP/kg	1.8
	POM, injection moulding	0.1 kg	0.6 OP/kg	0.6
	PA, injection moulding	0.3 kg	0.6 OP/kg	1.8
	ABS, injection moulding	0.6 kg	0.6 OP/kg	0.4
			Sub total:	**6.4**
All Transport	Truck (before and after use)	3 tkm	0.01 OP/tkm	0.03
			Sub total:	**0.0**
Use	Electricity (15 years* *52 weeks*1h/week*1000 W)	780 kWh	0.25 OP/kWh	195
	Paper (98 paper sacks * 50 g)	4.9 kg	0.9 OP/kg	4.41
			Sub total:	**199.4**
End-of-Life	Aluminium (cast, primary)	0.5 kg	0	0
Scenario: Incineration	steel tube (low alloy)	2 kg	0	0
	Polypropylene (PP)	3 kg	1.1 OP/kg	3.3
	POM	0.1 kg	1.0 OP/kg	0.1
	Polyamide (PA)	0.3 kg	1.1 OP/kg	3.3
	ABS (high impact)	0.6 kg	1 OP/kg	0.6
	electric motor (1000 W) (50% St, 50% Cu)	1 kg	0	0
	Rubber (calculated as PB)	0.3 kg	1.2 OP/kg	0.36
	textile sack (calculated as cotton)	0.5 kg	0.1 OP/kg	0.05
	card board	1 kg	0.4 OP/kg	0.4
			Sub total:	**8.1**
			TOTAL:	**234 OP**

Table 7.4 OPM evaluation of a vacuum cleaner

7.5.3 Result and conclusions

The result for the vacuum cleaner, a sporadically used active product, is given as a bar chart in **figure 7.5**. It looks quite similar to those from case 1. The use stage is again predominant for the overall result, and, again, electricity consumption is the main influence within the use stage. With about 20 % of the overall score, materials production is, though, important as well. (The EDIP figures in the stages were: Mat.:1.12, Mfg.:1.04, Tra.: 0.01, Use: 42.04, EoL: 1.20 mPET)

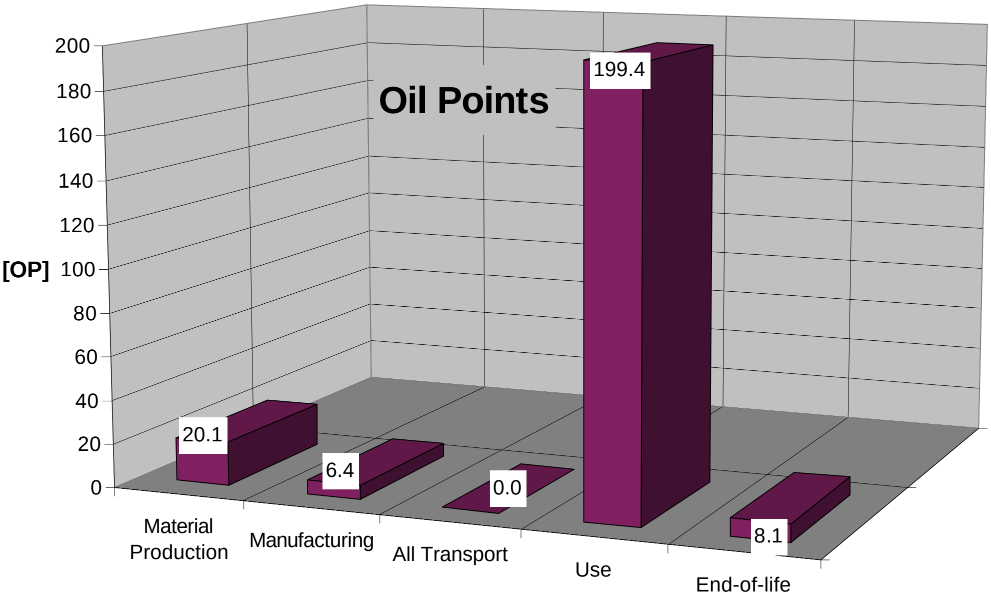


Figure 7.5 Oil Point bar chart result of the vacuum cleaner

This increased share is, however, more based on the fact that the vacuum cleaner is simply heavier than the coffee machine. If the vacuum cleaner would weigh about 2 kg (a fifth of its real weight) and have a life time of five years (a third of the expected value), like the coffee machine, it would score about 4 OP for Materials and 69 OP for Use. This still does not represent a substantial share of the overall score, especially not in relation to the electricity consumption.

The result for the vacuum cleaner, a sporadically used active product, is given as a bar chart on the left. It looks quite similar to the ones from case 1. The use stage is again predominant for the overall result, and . Again, electricity consumption is the main influence within the use stage. With about 20 % of the overall score, materials production is, though, of certain importance.

This increased share is, however, more based on the fact that the vacuum cleaner is simply heavier than the coffee machine. If the vacuum cleaner would weigh about 2 kg (a fifth of its real weight) and have a life time of five years (a third of the expected value), like the coffee machine, it would score about 4 OP for Materials and 69 OP for Use. This still does not represent a substantial share of the overall score, especially not in relation to the electricity consumption.

It can be concluded that the OPM is also valid for evaluations of sporadically used active products and that materials selection in this product group is not likely to have a substantial influence on the overall environmental performance.

7.6 Case 3: Two window frames

After validation of the OPM for active products in the first two case studies, this and the following case study concern the group of passive products.

The case study treats the same selection problem as described in Chapter 6, namely, the decision between wood or PVC with steel core as material for window frames. In Chapter 6, the example was used to explain the application of the OPM. In this chapter, however, the aim is to *validate* the OPM – again by comparing the OPM result with results from the two more complex methods. In all three evaluations the same data are used. These data were collected in the course of a full scale EDIP LCA as described in [Bey et al. 97].

In this case study, the way of assessing products by means of the EDIP method is explained in greater detail. The following subsections contain a description of the two product systems, comparisons of the corresponding Oil Point, Eco-indicator 95 and EDIP evaluations and a final conclusion on the window case.

7.6.1 Product system and Functional Unit

The product systems (depicted by the life cycle flow diagrams) of the two types of window frames were modelled on the basis of literature information and personal conversations with manufacturers and authorities conducted in [Bey et al. 97].

Main assumptions for the modelling are summarised below (most of them are based on statements from experts and/or market data):

- The frames are defined to have a standard size of 118 cm x 118 cm.
- For reasons of simplification, they are defined as non-openable because all elements of an opening mechanism are assumed to be similar for both frames and thus imply the same environmental impacts. For the same reason, neither the glass pane nor cleaning processes are included in the evaluation.
- The wooden frame is assumed to be painted every fifth year while the PVC frame is not treated at all during its life time.
- Manufacturing the plastic frame roughly requires 6 kg PVC plastic and 6 kg electroplated steel profile. The wooden frame mainly consists of about 9 kg wood.
- A life time of 40 years for each window frame is assumed. Use and disposal are defined to take place in Denmark. “Land filling” was determined as realistic disposal scenario as neither PVC frames nor wooden frames are allowed to be incinerated in Denmark.

The Functional Unit is defined as:

"Provision of a frame of 118 cm x 118 cm for a two-layer insulation glass pane in mechanically and optically good condition for 40 years in Denmark".

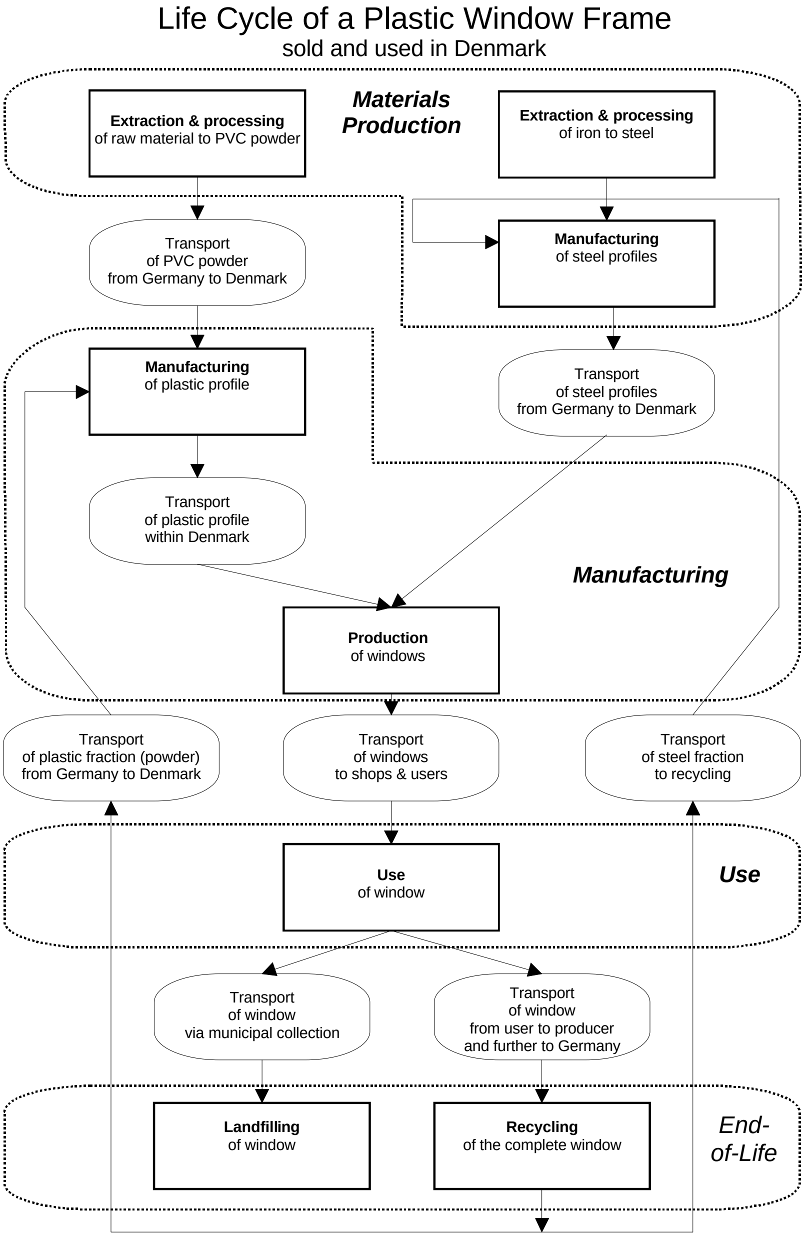


Figure 7.6 Life cycle model of a plastic window frame sold and used in Denmark

The life cycle of the plastic frame is depicted as flow diagram in **figure 7.6.**

Building blocks belonging to one of the four stages Materials Production, Manufacturing, Use or End-of-life are indicated by dotted lines. The sum of all transport processes represents a fifth stage.

The model comprises two routes of material production: one for the plastic body -consisting of about 6 kg mainly PVC - and the other for the steel profile - consisting of good 6 kg galvanised steel profile.

The steel profile is used to reinforce the window frame. Both routes meet in the manufacturing of the actual window.

In the Use stage - which is defined to last 40 years - the plastic frame is not treated at all apart from the negligible occasional washing combined with cleaning the window pane.

There are two possible end-of-life scenarios for the plastic frame: The by far largest number of frames in Denmark is disposed of via municipal waste collection and subsequent landfilling.

Alternatively, it is possible for the producer to collect the frames and send them to recycling to Germany where a system for recycling of PVC-frames is emerging [FREI 96].

The recycling scenario, however, is not taken into account here because only less than 1 % of all frames in Denmark is recycled [VSO, 1997].

A model of the life cycle of the wooden frame is given in **figure 7.7** on the left.

Generally, the transport processes in all described life cycles are calculated as a separated phase in order to mirror possible influences of long-distance transports involved in the life cycles. Concerning these transport data, it is interesting that most processes of the plastic frame's life cycle happen in Denmark and Germany, while respective countries for the wooden frame are Finland and Denmark.

The material production for the wooden frame, i.e. harvesting, sawing, drying, etc. of lumber, takes place in Finland. Via train and ship, the lumber is then transported to Denmark where pressure water-proof wooden frames and subsequently whole, painted windows are produced.

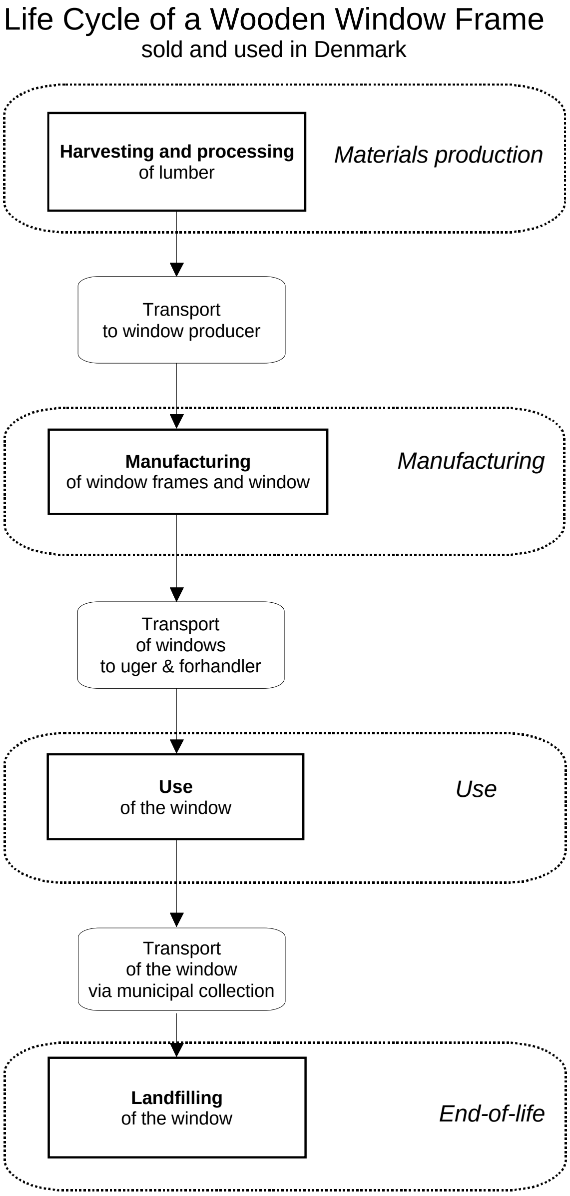


Figure 7.7 Life cycle of a wooden window frame sold and used in Denmark

The windows are either transported to shops or directly to the user. The difference, however, is not significant. During use, the windows are painted every fifth year in the life time of 40 years, summing-up to a total of nine times painting. Due to chemicals involved in the pressure impregnation, also wooden frames are disposed of by landfilling.

<u>Summary of the models of the two frames:</u>

- Both: Life time 40 years, disposal via landfilling
- Plastic: production from primary material, no treatment during use
- Wood: pressure impregnated core wood, painting every fifth year

7.6.2 The EDIP models and evaluation results

When Goal and Scope are defined, including a model of the product system and a Functional Unit, the next step in a Life Cycle Assessment is to make an Inventory of all inputs and outputs of the system. This is done by adding all inputs and outputs of the single processes in the product system.

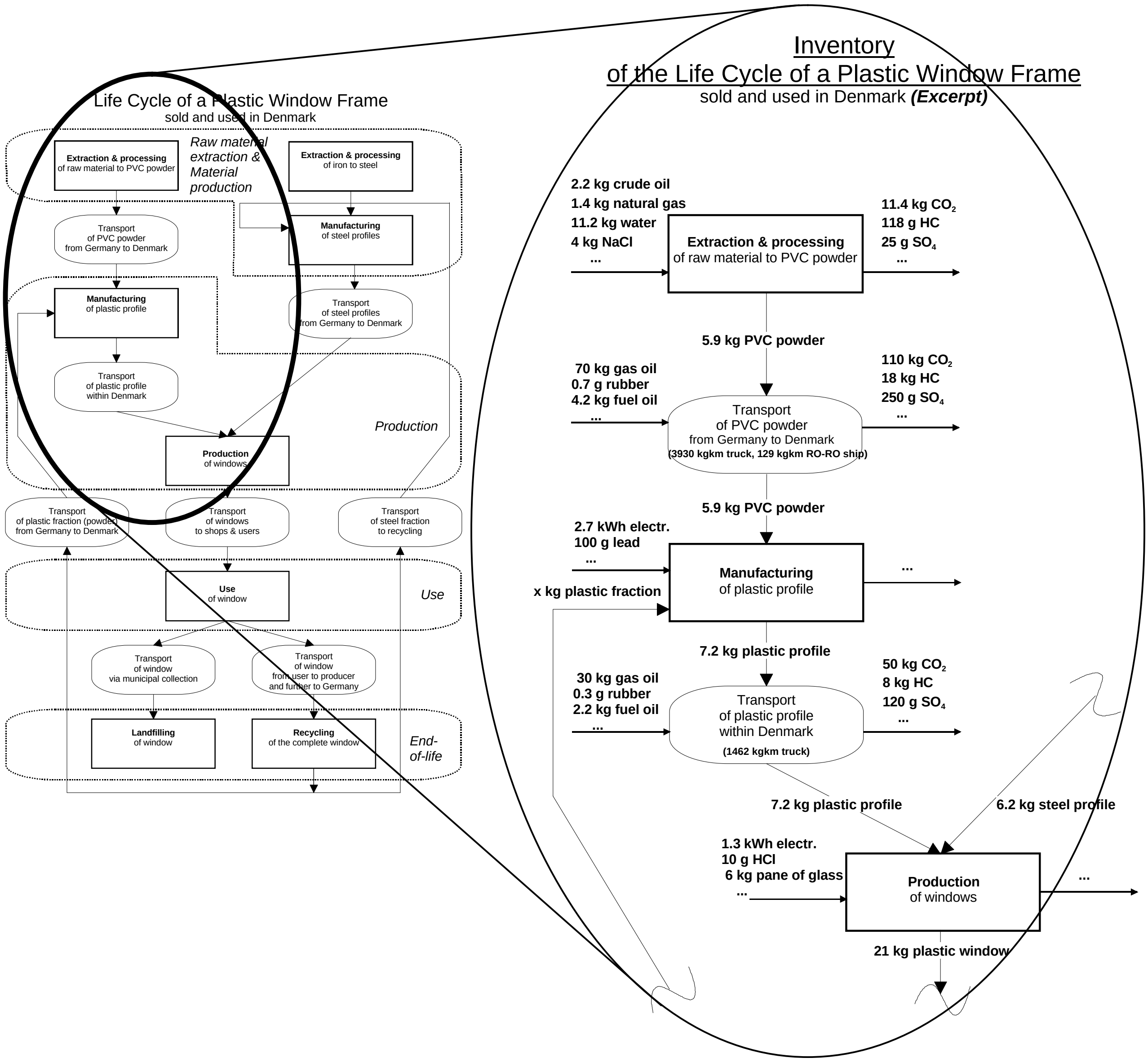


Figure 7.8 Excerpt of the Inventory for a plastic window frame

Depending on the degree of complexity of the product model and the data quality required, the amount of information gathered in such an Inventory can be relatively high – and this is often the case.

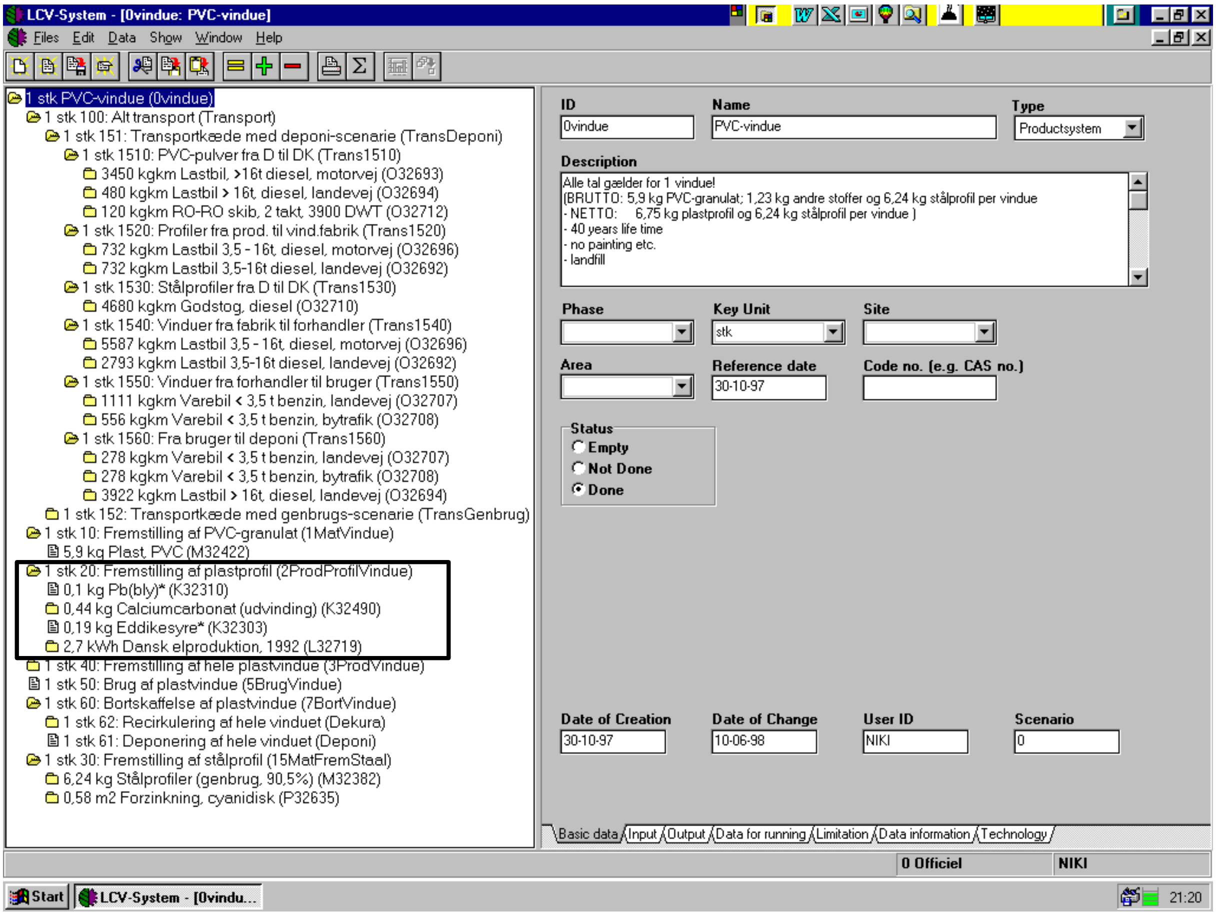
In order to give an impression of this most comprehensive and time consuming element of a full scale LCA, an excerpt of the data for the plastic frame is depicted in **figure 7.8**.

Data sources were mainly manufacturers, particular business organisations, the EDIP process data base and individual persons. Such an Inventory was made for both frames.

It shall be mentioned here that the quality of any Inventory is highly dependent on the quality of the data sources used: Usage of many assumptions and average data - which usually has to be done due to lack of process-specific data - makes the resulting Inventory to a less precise recording of the real processes. Resulting influences on the overall result, however, can be taken into account in the scope of a subsequent Sensitivity Analysis. This, of course, cannot improve the data quality as such but it may preserve from drawing, for example, too far-reaching conclusions.

The next step in the case studies is the evaluation of the products with basis on the Inventory data. As in all comparative cases mentioned here, again all evaluations involve the same respective life cycle and Inventory. For the EDIP evaluation, the LCV-tool - (version 2.06 beta) was used to model the life cycle and to make an Impact Assessment.

The model of the plastic frame’s life cycle - designed with the EDIP-tool - is shown below (**fig. 7.9**). In this computer tool, the life cycle of the product is modelled in a way, which is comparable to standard Windows^{TM} file management utilities. The product folder contains folders for the five life cycle stages, which, in turn, contain sub-processes (e.g. the building blocks of figure 7.8) or direct exchanges with the environment.



```
1 stk PVC-vindue (0vindue)
  1 stk 100: Alt transport (Transport)
    1 stk 151: Transportkæde med deponi-scenarie (TransDeponi)
      1 stk 1510: PVC-pulver fra D til DK (Trans1510)
        3450 kgkm Lastbil, >16t diesel, motorvej (O32693)
        480 kgkm Lastbil > 16t, diesel, landevej (O32694)
        120 kgkm RO-RO skib, 2 takt, 3900 DWT (O32712)
      1 stk 1520: Profiler fra prod. til vind.fabrik (Trans1520)
        732 kgkm Lastbil 3,5 - 16t, diesel, motorvej (O32696)
        732 kgkm Lastbil 3,5-16t diesel, landevej (O32692)
      1 stk 1530: Stålprofiler fra D til DK (Trans1530)
        4680 kgkm Godstog, diesel (O32710)
      1 stk 1540: Vinduer fra fabrik til forhandler (Trans1540)
        5587 kgkm Lastbil 3,5 - 16t, diesel, motorvej (O32696)
        2793 kgkm Lastbil 3,5-16t diesel, landevej (O32692)
      1 stk 1550: Vinduer fra forhandler til bruger (Trans1550)
        1111 kgkm Varebil < 3,5 t benzin, landevej (O32707)
        556 kgkm Varebil < 3,5 t benzin, bytrafik (O32708)
      1 stk 1560: Fra bruger til deponi (Trans1560)
        278 kgkm Varebil < 3,5 t benzin, landevej (O32707)
        278 kgkm Varebil < 3,5 t benzin, bytrafik (O32708)
        3922 kgkm Lastbil > 16t, diesel, landevej (O32694)
    1 stk 152: Transportkæde med genbrugs-scenarie (TransGenbrug)
  1 stk 10: Fremstilling af PVC-granulat (1MatVindue)
    5,9 kg Plast, PVC (M32422)
  1 stk 20: Fremstilling af plastprofil (2ProdProfilVindue)
    0,1 kg Pb(bly)* (K32310)
    0,44 kg Calciumcarbonat (udvinding) (K32490)
    0,19 kg Eddikesyre* (K32303)
    2,7 kWh Dansk elproduktion, 1992 (L32719)
  1 stk 40: Fremstilling af hele plastvindue (3ProdVindue)
  1 stk 50: Brug af plastvindue (5BrugVindue)
  1 stk 60: Bortskaffelse af plastvindue (7BortVindue)
    1 stk 62: Recirkulering af hele vinduet (Dekura)
    1 stk 61: Deponering af hele vinduet (Deponi)
  1 stk 30: Fremstilling af stålprofil (15MatFremStaal)
    6,24 kg Stålprofiler (genbrug, 90,5%) (M32382)
    0,58 m2 Forzinkning, cyanidisk (P32635)
```

ID: 0vindue
Name: PVC-vindue
Type: Productsystem

Description:
Alle tal gælder for 1 vindue!
(BRUTTO: 5,9 kg PVC-granulat; 1,23 kg andre stoffer og 6,24 kg stålprofil per vindue
- NETTO: 6,75 kg plastprofil og 6,24 kg stålprofil per vindue)
- 40 years life time
- no painting etc.
- landfill

Phase:
Key Unit: stk
Site:
Area:
Reference date: 30-10-97
Code no. (e.g. CAS no.):

Status
○ Empty
○ Not Done
● Done

Date of Creation: 30-10-97
Date of Change: 10-06-98
User ID: NIKI
Scenario: 0

0 Officiel
NIKI

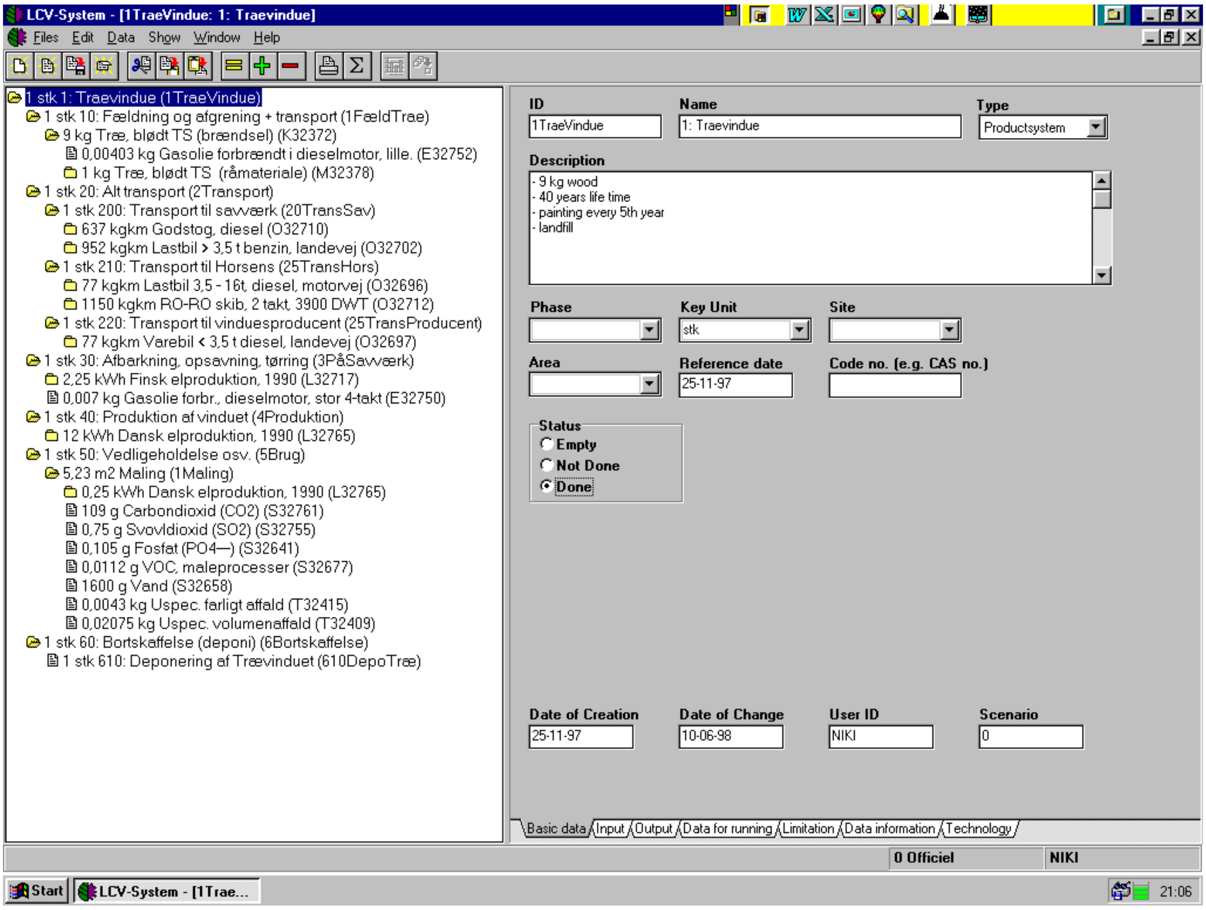
Figure 7.9 The life cycle of the plastic frame designed with the EDIP LCV-tool (Danish text used in the model)

For example, the manufacturing of the plastic profile (in Danish: ”fremstilling af plastprofil”) from 5.9 kg PVC-granulate requires - among other things - 2.7 kWh electricity as input (see rectangular in figure 7.7). As manufacturing of the frame takes place in Denmark, a Danish electricity production scenario was chosen in the model.

Danish electricity is a pre-defined process which, in turn, involves a number of inputs and outputs. About 750 of such processes and exchanges are pre-defined in the latest version (2.11 beta, 1999) of the LCV-tool.

For the calculations in the LCV-tool, the sequence of stages in the model is not relevant. Due to this circumstance, the models in figure 5 and 6 are acceptable although the sequence of stages may not represent the real one. The important thing is not the sequence but the contents of the stage folders.

The LCV model of the life cycle of the wooden frame is depicted in **figure 7.10** below.



- 1 stk 1: Traevindue (1TraeVindue)
  - 1 stk 10: Fældning og afgrening + transport (1FældTrae)
    - 9 kg Træ, blødt TS (brændsel) (K32372)
      - 0,00403 kg Gasolie forbrændt i dieselmotor, lille. (E32752)
      - 1 kg Træ, blødt TS (råmateriale) (M32378)
  - 1 stk 20: Alt transport (2Transport)
    - 1 stk 200: Transport til savværk (20TransSav)
      - 637 kgkm Godstog, diesel (O32710)
      - 952 kgkm Lastbil > 3,5 t benzin, landevej (O32702)
    - 1 stk 210: Transport til Horsens (25TransHors)
      - 77 kgkm Lastbil 3,5 - 16t, diesel, motorvej (O32696)
      - 1150 kgkm RO-RO skib, 2 takt, 3900 DWT (O32712)
    - 1 stk 220: Transport til vinduesproducent (25TransProducent)
      - 77 kgkm Varebil < 3,5 t diesel, landevej (O32697)
  - 1 stk 30: Afbarkning, opsavning, tørring (3PåSavværk)
    - 2,25 kWh Finsk elproduktion, 1990 (L32717)
    - 0,007 kg Gasolie forbr., dieselmotor, stor 4-takt (E32750)
  - 1 stk 40: Produktion af vinduet (4Produktion)
    - 12 kWh Dansk elproduktion, 1990 (L32765)
  - 1 stk 50: Vedligeholdelse osv. (5Brug)
    - 5,23 m2 Maling (1Maling)
      - 0,25 kWh Dansk elproduktion, 1990 (L32765)
      - 109 g Carbondioxid (CO2) (S32761)
      - 0,75 g Svovldioxid (SO2) (S32755)
      - 0,105 g Fosfat (PO4—) (S32641)
      - 0,0112 g VOC, maleprocesser (S32677)
      - 1600 g Vand (S32658)
      - 0,0043 kg Uspec. farligt affald (T32415)
      - 0,02075 kg Uspec. volumenaffald (T32409)
  - 1 stk 60: Bortskaffelse (deponi) (6Bortskaffelse)
    - 1 stk 610: Deponering af Trævinduet (610DepoTræ)

ID: 1TraeVindue
Name: 1: Traevindue
Type: Productsystem

Description:
- 9 kg wood
- 40 years life time
- painting every 5th year
- landfill

Phase:
Key Unit: stk
Site:
Area:
Reference date: 25-11-97
Code no. (e.g. CAS no.):

Status
○ Empty
○ Not Done
● Done

Date of Creation: 25-11-97
Date of Change: 10-06-98
User ID: NIKI
Scenario: 0

0 Officiel
NIKI

Figure 7.10 The life cycle of the wooden frame designed with the EDIP-tool (model with Danish text)

Both EDIP models were used for environmental Impact Assessments. This means that the Inventory data were characterised, normalised and finally weighted. All these steps were done by the EDIP-tool.

It shall be stressed here that the presented case studies exclusively consider potential impacts on the *natural environment*. The reason for this is that aspects of resource depletion and working environment - which are considered in the EDIP methodology and thus are automatically calculated as well - are not considered in the other two evaluation methods utilised in the case studies.

In the EDIP method, results of Impact Assessments, i.e. values for weighted environmental impact potentials, are usually given as a bar chart of contributions to environmental impact categories. Such a typical bar chart is shown below (**fig. 7.11**). Each contribution is expressed in "**t**argeted" **m**illi-**p**erson **e**quivalents, mPET.

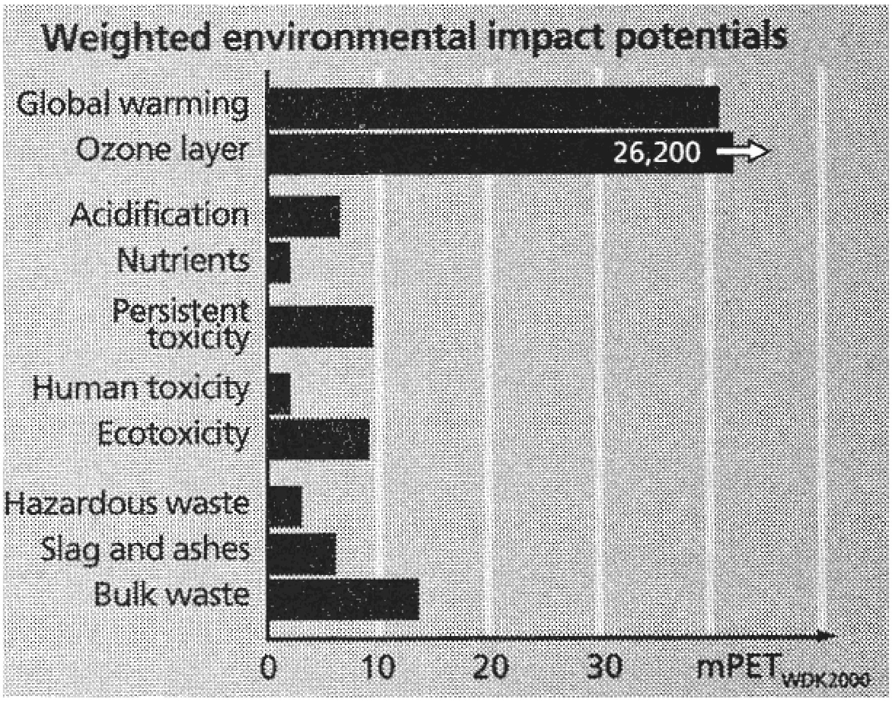


Figure 7.11 A typical EDIP bar chart result [Wenzel et al. 97]. This chart shows weighted environmental impact potentials for a refrigerator.

Single figure summation as exception for EDIP

Characterising, Normalising, and subsequent Weighting of the Inventory data resulted in a set of mPET-values (targeted milli-person equivalents) for 15 environmental impact categories. These amounts of mPETs were then summarised for each life cycle stage and for the overall result in order to get one single value and thus make results of the EDIP methodology comparable to the other methods (These summations - for the single stages and for the total life cycle, however, are not part of the methodology. They were solely included to facilitate a comparison with the other methods).

Table 7.5 shows an LCV- print out of the environmental contributions from all stages of the plastic/steel frame.

Environmental Result	**Calculation for Plastic Window**			
0vindue	PVC-window			
EDIP level:	Weighting			
Quantity:	1			
Lifetime [years]:	40			
Weighting 1:	Yes			
Effect-ID	Name	Life Cycle Stage	Quantity	Unit
1	Global Warming	MATERIALS PRODUCTION	0.074230	mPET
10	Human TOX, water	MATERIALS PRODUCTION	0.026650	mPET
11	Human TOX, air	MATERIALS PRODUCTION	0.010160	mPET
12	Human TOX, soil	MATERIALS PRODUCTION	0.010540	mPET
14	Eco TOX, water-chronic	MATERIALS PRODUCTION	0.018680	mPET
15	Eco TOX, water -acute	MATERIALS PRODUCTION	0.042950	mPET
16	Eco TOX, soil	MATERIALS PRODUCTION	0.092620	mPET
20	Bulk waste	MATERIALS PRODUCTION	0.046220	mPET
21	Hazardous waste	MATERIALS PRODUCTION	1.290000	mPET
22	Radioactive waste	MATERIALS PRODUCTION	0	mPET
23	Slag and ashes	MATERIALS PRODUCTION	0.010830	mPET
3	Acidification	MATERIALS PRODUCTION	0.055560	mPET
4	Photochemical ozon-1 (low NOx)	MATERIALS PRODUCTION	0.002229	mPET
5	Photochemical ozon-2 (high NOx)	MATERIALS PRODUCTION	0.001935	mPET
6	Nutrient enrichment	MATERIALS PRODUCTION	0.017380	mPET
		Sub-total:	1.699984	mPET
1	Global Warming	MANUFACTURING	0.014680	mPET
10	Human TOX, water	MANUFACTURING	0.008671	mPET
11	Human TOX, air	MANUFACTURING	0.001325	mPET
12	Human TOX, soil	MANUFACTURING	0.006441	mPET
14	Eco TOX, water-chronic	MANUFACTURING	0.008543	mPET
15	Eco TOX, water -acute	MANUFACTURING	0.007964	mPET
16	Eco TOX, soil	MANUFACTURING	0.000020	mPET
20	Bulk waste	MANUFACTURING	0.012420	mPET
21	Hazardous waste	MANUFACTURING	0.000000	mPET
22	Radioactive waste	MANUFACTURING	0	mPET
23	Slag and ashes	MANUFACTURING	0.008080	mPET
3	Acidification	MANUFACTURING	0.007186	mPET
4	Photochemical ozon-1 (low NOx)	MANUFACTURING	0.000360	mPET
5	Photochemical ozon-2 (high NOx)	MANUFACTURING	0.000380	mPET
6	Nutrient enrichment	MANUFACTURING	0.001816	mPET
		Sub-total:	0.077885	mPET
1	Global Warming	TRANSPORT	0.016260	mPET
10	Human TOX, water	TRANSPORT	0.000874	mPET
11	Human TOX, air	TRANSPORT	0.013320	mPET
12	Human TOX, soil	TRANSPORT	0.000189	mPET
14	Eco TOX, water-chronic	TRANSPORT	0.000683	mPET
15	Eco TOX, water -acute	TRANSPORT	0.000001	mPET
16	Eco TOX, soil	TRANSPORT	0.000000	mPET
20	Bulk waste	TRANSPORT	0.000312	mPET
21	Hazardous waste	TRANSPORT	0.000000	mPET
22	Radioactive waste	TRANSPORT	0	mPET
23	Slag and ashes	TRANSPORT	0.000296	mPET
3	Acidification	TRANSPORT	0.011750	mPET
4	Photochemical ozon-1 (low NOx)	TRANSPORT	0.012260	mPET
5	Photochemical ozon-2 (high NOx)	TRANSPORT	0.012660	mPET
6	Nutrient enrichment	TRANSPORT	0.007188	mPET
		Sub-total:	0.075792	mPET
20	Bulk waste	End-of-life Sub-total:	0.325200	mPET
		Total:	2.178862	mPET

Table 7.5 The figures behind the EDIP bar chart result for the plastic window frame and their summation in stages and in total (A Use stage is not included in the model because there are no exchanges occurring) The summations are NOT part of the EDIP method.

(Remark: In none of the case studies radioactive waste - resulting from nuclear power production - was taken into account, due to technical problems.)

The data on the next page therefore specify always a zero for radioactive waste. The deviation in the result is not significant, due to the fact that primarily Danish, i.e. non-nuclear, electricity is used in the models and because this exclusion was done in all cases.)

A similar summarisation was performed for the wooden frame, as well. This one, however, is only reflected in **table 7.6** below. It shows the results of the summarised EDIP evaluation of the two window frames in mPETs. In order not to set exceeding focus on decimal places, all figures are rounded to one decimal.

	Materials Production	**Manu-facturing**	**Transport**	**Use***	**End-of-life**	**Total**
	[mPET]	[mPET]	[mPET]	[mPET]	[mPET]	[mPET]
Plastic	1.7	0.1	0.1	0	0.3	**2.2**
Wood	> 0.0 $^{\supseteq}$	0.2	0.1	0	0.1	**0.4**

Table 7.6 Summarised EDIP results for a plastic and a wooden frame

* "Pressure impregnating" of the wood is not included due to lack of data. This is probably important, see App. III

Plastic frame
According to the figures in table 7.6, the plastic frame performs worse than the wooden frame. This is mostly due to the Materials Production. Background for this circumstance is the fact that the plastic material extraction (primary material) and processing cause a considerable amount of hazardous waste (1.29 mPET, see tab. 7.5). Manufacturing and Transport of the plastic frame result in no significant environmental harm.

Disposal of the plastic frame by landfill causes an amount of bulk waste which corresponds to 0.33 mPETs. A disposal scenario with incineration would have resulted in a considerably higher value due to the fact that the plastic frame mostly consists of PVC which in turn causes the well-known problematic emissions (highly dangerous chloride compounds (e.g. hydrochloric acid), dioxins and heavy metals [DEPA, 1996]).

Wooden frame
The Manufacturing stage in the wooden frame's life cycle has a considerably high electricity consumption per frame which results in about twice as many mPETs as any other stage of this product. Compared to the plastic frame, Manufacturing of the wooden frame

causes about twice as many mPETs. Due to lack of data, the process of pressure impregnating of the wood is not included in the evaluation.

The actual figure for the Material Production stage will thus be higher.

7.6.3 The Eco-indicator 95 evaluation results

In the Eco-indicator "Manual for Designers" [Goedkoop 95b], various indicators for materials, manufacturing processes, transport processes and other processes are pre-defined in specific units, e.g. milli points per kg, milli points per kWh. Those milli-points can be compared to the mPETs from the EDIP methodology. There are, however, substantial differences e.g. in the utilised bases for Normalisation and Weighting (see section 3.3.2).

Using the life cycle models and Inventories from section 7.6.1 suitable pre-defined Eco-indicators could be found and were multiplied by the respective amounts of e.g. processed material.

As an example, the calculation of the value for the Material Production of the plastic frame shall be described by means of **table 7.7** below (figures rounded to one decimal place). It is important to keep in mind that the output of this stage are semi-finished products, namely a galvanised steel profile and PVC granulate. They are inputs to the actual Manufacturing of the frame.

Stage: MATERIALS PRODUCTION

Material or Process	**Quantity**	**Eco-indicator**	**Result**
PVC-granulate (primary)	5.9 kg	4.2 mp/kg	24.8 mp
secondary steel	6.2 kg	1.3 mp/kg	8.1 mp
rolling, warm *	0.58 m^2	2.0 mp/ m^2	1.2 mp
Electroplating	0.58 m^2	22 mp/ m^2	12.8 mp
		Sub-total:	**46.9 mp**

Table 7.7 Use of Eco-indicators for the quantification of environmental damage, shown by means of the material production for a plastic window frame

When certain indicators could not be found in the manual [Goedkoop 95b], worst-case oriented indicators were estimated wherever possible based on existing indicators. This was for instance done for the production of the steel profiles by warm rolling, which is not pre-defined (see the asterisk * in table T). In this case, an estimation was made which was based on cold-rolling of steel (0.46 mp/ m^2). Due to the assumed higher energy consumption compared to cold rolling, the value was set higher (by a factor of about four).

Such results - amounts of milli points for each stage - could finally be summarised to one score for the whole life cycle. This procedure is defined in the methodology. The comparative result of this evaluation is given in **table 7.8** on the following page.

	Materials Production.	**Manu-facturing**	**Transport**	**Use**	**End-of-life**	**Total**
	[mp]	[mp]	[mp]	[mp]	[mp]	[mp]
Plastic	46.9	2.5	7.0	0	5.5	**61.8**
Wood	$> 8.2^{\supseteq}$	8.0	0.5	4.5	0.2	**21.4**

Table 7.8 Summarised Eco-indicator results for the plastic and the wooden frame (“Pressure impregnating“ of the wood is not included due to lack of data. Estimates for end-of-life are based on similar existing indicators)

The figures of table 7.8 show a better environmental result for the wooden frame than for the plastic one. The result for the wooden frame, however, is rather insecure due to the omission of “pressure impregnation” and the two estimations for Use and Disposal.

Plastic frame

Materials Production is the biggest source of impact potentials in the plastic frame’s life cycle due to the utilisation of primary material. The Manufacturing involves about 3 kWh electricity per frame, which is not significantly much. This is mirrored in the relatively low mp-value.

Transport, however, results in the second highest mp-value. The biggest contribution to this result comes from about 20 ton-kilometres (tkm) truck transport which are equal to 6.77 mp. Train and ship transport have considerably lower indicators (about 1/10 of truck transport) and contribute only with a total of 4.8 tkm.

Wooden frame

The most important contributions to the wooden frame’s Materials Production stage are the mechanical wood processes (nearly 7 mp) and the drying of the wood (1.5 mp). The high energy consumption of the Manufacturing stage (about 12 kWh/frame and 0.67 mp/kWh) characterises this stage.

The wooden frame weighs about two thirds of the plastic/steel frame, involves a lot of efficient ship transport and is transported over relatively short distances. This is the reason for the comparatively low figure for Transport.

Painting of the frame (9 times or 5 m^2 in total) in the Use stage and landfilling in the End-of-life stage of the frame are not defined with Eco-indicators.

While for painting an indicator of 0.1 mp/m^2 had to be guessed (due to missing comparable ones), the indicator for landfill could be estimated by means of other disposal processes. The indicator for painting may well be much higher, which lets this stage appear to probably be the most important one of the wooden frame's life cycle.

7.6.4 The Oil Point evaluation results

The two complete Oil Point evaluations are shown in the tables below.

Life cycle stage	Material or Process	Amount	OP-indicator	Result
Material	plastic-granulate	6 kg	1.5 OP/kg	9.0 OP
Production	electroplated steel	6 kg	0.7 OP/kg *	4.2 OP
Manufacturing	electricity	3.7 kWh	0.25 OP/kWh	0.9 OP
All Transport	truck transport	20 tkm	10 OP/1000 tkm	0.2 OP
Use	-	-	-	0 OP
End-of-life	-	-	-	0 OP
			TOTAL:	**14.3 OP**

Table 7.9 Use of Oil Point indicators for the quantification of potential environmental impact, shown by means of a plastic window frame

* The indicator for electroplated steel is estimated based on the plastic-granulate indicator. Similar estimations based on data from literature and experience are explicitly allowed in the method.

The OPM result determines Materials Production as the by far most important stage of the plastic frames' life cycle. Within this stage, it is the (primary) plastic-granulate which is responsible for about two thirds of the energy requirements.

The estimated rest is necessary for the steel production and its electroplating. The major part of the electricity (2.7 kWh) is used for producing the actual profile. Only about 1 kWh goes into the window frame production, i.e. into cutting and welding of frame elements. Use and End-of-life of the window frames are not connected to any significant energy consumption.

The complete calculation for the wooden frame is shown in **table7.10**.

Life cycle stage	Material or Process	Amount	OP-indicator	Result
Materials	wood	9 kg	0.1 OP/kg	0.9 OP
Production	electricity (for drying)	2.3 kWh	0.25 OP/kWh	0.6 OP

Manufacturing	electricity (processes)	12 kWh	0.25 OP/kWh	3 OP
All Transport	truck transport	1.1 tkm	10 OP/1000 tkm	≈ 0 OP
Use	-	-	-	0 OP
End-of-life	-	-	-	0 OP
			TOTAL:	**4.5 OP**

Table 7.10 The Oil Point result for the wooden window frame

According to this calculation, Materials Production results in about one third of the overall potential environmental impact. The most relevant stage, however, is Manufacturing where a considerable amount of electrical energy is required.

Comparing the two materials for the window frame, also the Oil Point evaluation indicates wood as the preferable material.

7.6.5 Summarised result and conclusions

For the overall conclusion upon the validity of the OPM for rough evaluations, a comparison of the two Oil Point results with the results obtained by means of the other two methods is necessary. This is done in table 7.11, which is a summary of all previous results in the Window frame case.

	Window Frames					
	Plastic			Wood		
	EDIP [mPET]	E.-i. 95 [mp]	OPM [OP]	EDIP [mPET]	E.-i. 95 [mp]	OPM [OP]
Materials Production	1.7	46.9	13.2	> 0.0	> 8.2	1.5

Manufacturing	0.1	2.5	0.9	0.2	8.0	3
All Transport	0.1	7.0	0.2	0.1	0.5	0
Use	0	0	0	0	4.5	0
End-of-life	0.3	5.5	0	0.1	0.2	0
Total:	**2.2**	**61.9**	**14.3**	**0.4**	**21.4**	**4.5**
Heat loss during Usage (40 x 15 kg oil*)	1087	4050	600	1087	4050	600

Table 7.11 Comparison of the results of the window frame case (*: estimated)

This table summarises the results of all three evaluations on the window frame case, separated into life cycle stages. The results are presented as bar charts in **figure 7.12**.

The methods correlate in their overall results: In all three evaluations, the wooden frame performs better than the one made of plastic/steel. The score for wood is in each case about a third of the comparable score for plastic with steel core. For both alternatives, the tendency of importance of the different stages for the overall result is similar for both the OPM figures and for the EDIP figures.

The Use stage of the frame does not have major direct environmental consequences. There are, however, indirect consequences: the last row of table 7.11 gives method-specific figures for an estimated amount of thermal energy that is lost through the window *pane* over the whole life time of 40 years (15 kg oil each year). This enlarged comparison shows that the impact caused by the loss of energy through the glass pane is between 40 and 2700 times as big as the environmental impact caused by the frame as such! The difference between the two materials and process chains for a window frame is thus negligible in relation to the overall performance of the product.

In other words: environmental optimisation of window frames is by far less important than environmental optimisation of whole windows!

Seen in this holistic scope, the major environmental impact of the *whole window* occurs indirectly during the use stage. This is remarkable in so far, as also the whole window is a passive product (because the main functionality of the product does not require anything but muscle power). As the first two cases studies proved, the importance of the Use stage is often related to energy consumption during usage (see also [Dannheim et al. 97]).

If one would decide to concentrate on the material for the frame anyway, the thermal conductivity of a candidate material would be a property to focus on.

The evaluations presented were focused on the frame, where wood performs better than plastic in this specific case, a holistic contemplation leads to the conclusion that the selection of a different type of *glass* would be much more appropriate in order to improve the overall environmental performance. A frame as such – even if environmentally benign in itself – has to be seen as *part* of a more complex system which consequently has to be evaluated as a whole. A car door or a seat in a train would be other examples of the same sort.

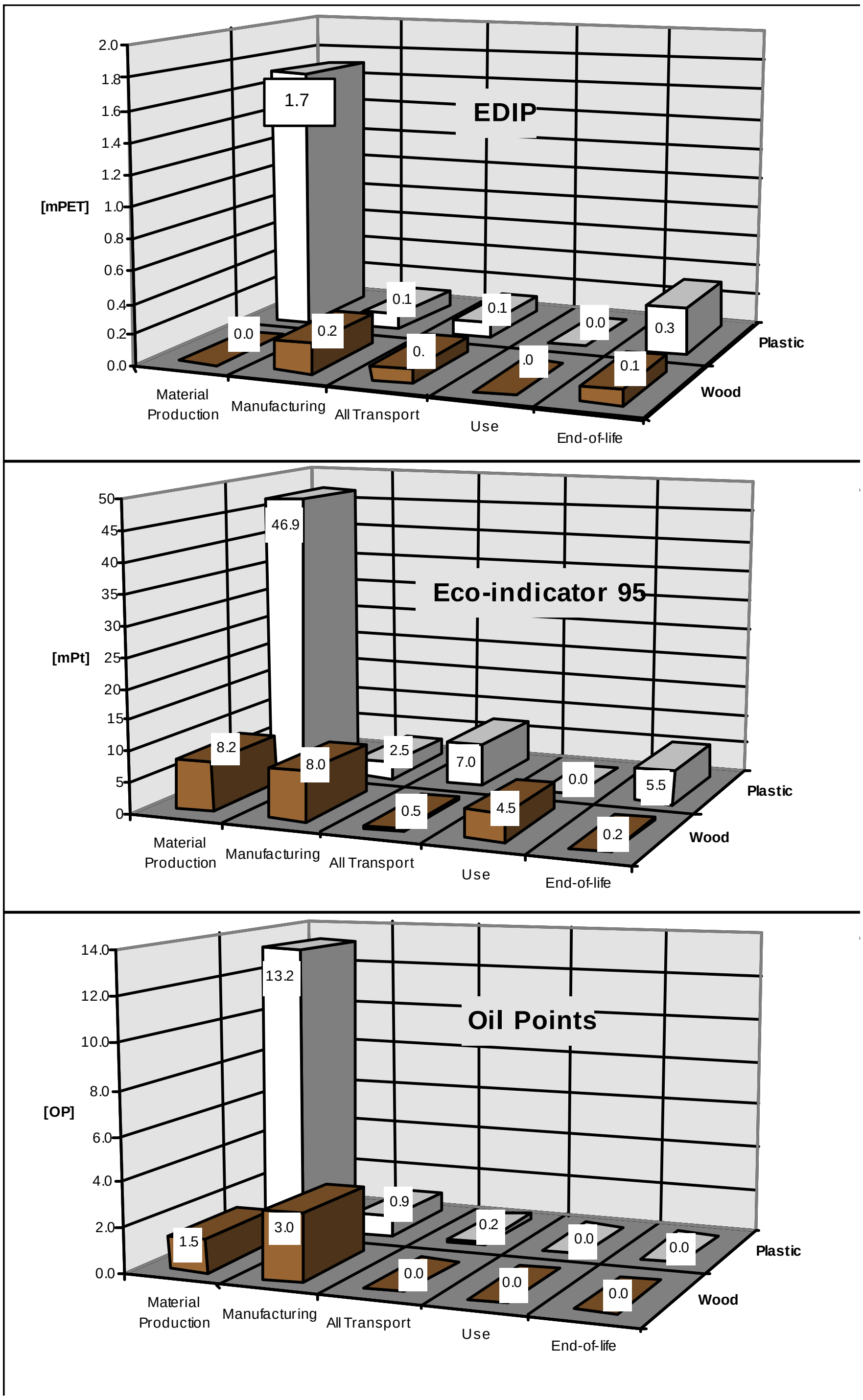


Figure 7.12 Results of case studies comparing three methods of decreasing complexity (from top to bottom) by means of window frames in wood vs. in PVC with steel core.

Other scenarios

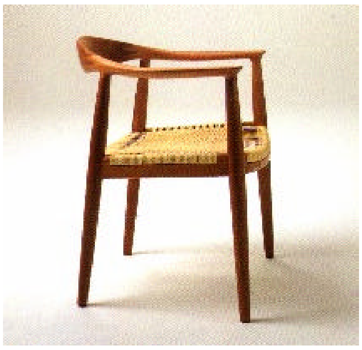
It may seem that the main result - i.e. that wood performs better than plastic - is dependent on the assumed life cycle of the product.

However, in a brief evaluation with a scenario where recycled material is used, which then would be recycled again, the scores for the PVC/steel frame would be about halved but still be higher than the scores of the wooden frame. Also an end-of-life scenario involving incineration would not invert the main result, as both alternatives would score higher but the plastic steel solution higher than the wooden solution. The omission of "pressure impregnating"and painting in the Manufacturing stage of the wooden frame is the only factor that could influence the main result to be in favour of the plastic solution, because it is a factor only on the wooden solution's side. This potential influence, however, is assumed to be small and of no importance for the main result, either. Pressure impregnated wood is, however, on the list of undesirable substances given in App. III.

Concerning the validation of the OPM, it can thus be stated that the method is valid in this case of passive products. The final validation for all passive products shall be done after the following second case study on passive products.

7.7 Case 4: A chair

This case study deals with a piece of furniture: a dining chair. The product integrates sophisticated craftsmanship, comfortable forms and high-quality materials, which makes it a timeless product held in high esteem by its owners. As the chair is to be used indoors, physical ageing of the product is reduced to a minimum. High notional value and low wear let this product have an expected life time of a hundred years. (The chair, model PP 501, was first produced in 1949. Thus half of this life time has probably already been reached by some examples.)



The chair, model PP 501 (seat material: cane)

Both the OPM and the EDIP evaluation were conducted in the scope of a Master's project [Lucchetta 99] in collaboration with the furniture company PP Møbler A/S in Allerød, Denmark.

7.7.1 Product system and Functional Unit

The chair has a total weight of 6.4 kg and is manufactured from different kinds of wood, the majority of which come from Denmark (82 wt % of the finished product). Other materials used for the manufacturing are polyurethane foam and leather fore the seat (model PP 503) respectively hand-woven cane (model PP 501), as well as glue and a tiny amount of brass. As surface finish, the wooden parts are treated with a soap solution. The chair is mostly sold to European customers, while the rest is sold to overseas markets including Japan.

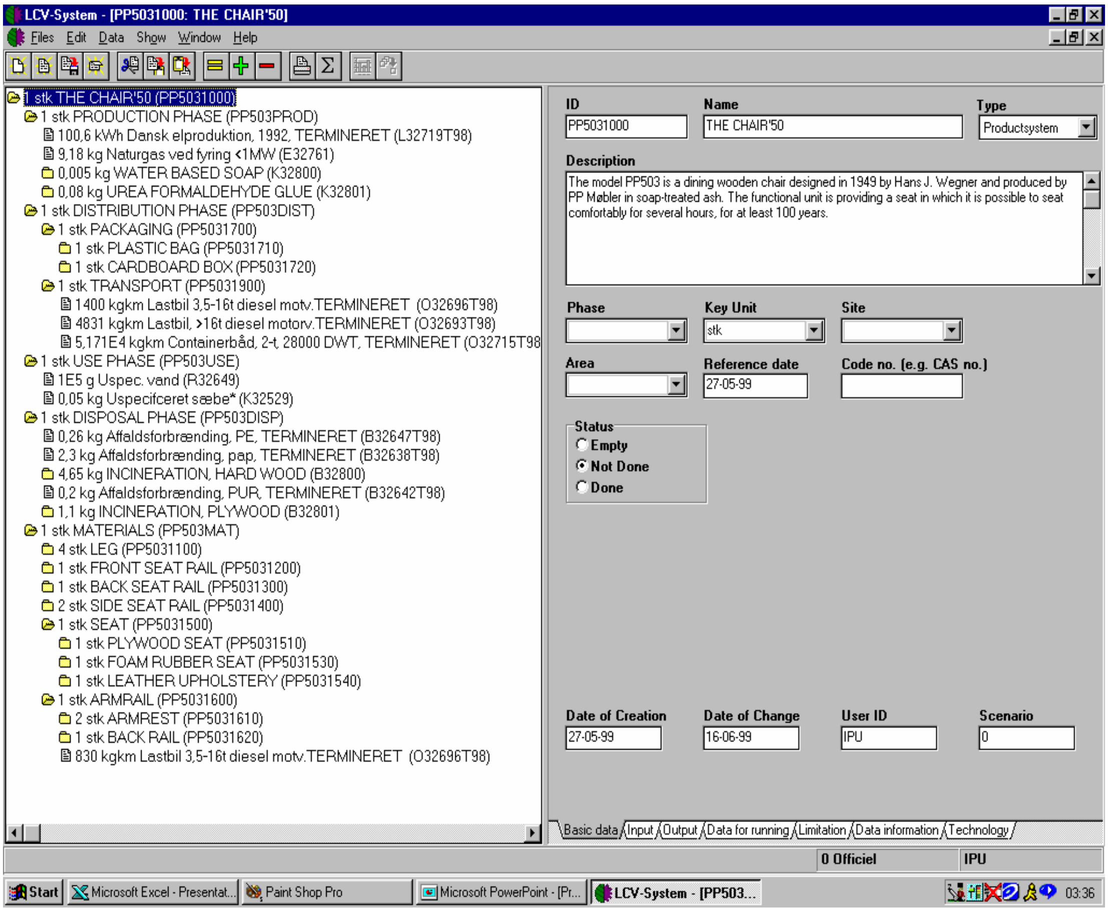
THIS CASE INCORPORATES THE INITIAL OP-CALCULATION PRINCIPLE FOR THE END-OF-LIFE STAGE, SEE SECTION 6.7. NEVERTHELESS, THE CASE IS INCLUDED AS IT IS STILL CONSIDERED A USEFUL EXAMPLE.

The evaluations shown below focus on the model with leather seat (PP 503) and soap surface treatment. Scenarios for the cane seat model and a lacquer surface treatment are performed later. The Functional Unit is defined as *"Provision of a 45 cm high seat with armrests in which it is possible to sit comfortably for several hours and which can last a hundred years. The product being sold and used in Europe."*

The chair, model PP 503 (seat material: leather)

7.7.2 EDIP and OPM evaluations

The EDIP evaluation was done by means of the LCV-tool. A screen shot of the product model is given below.



```
1 stk THE CHAIR'50 (PP5031000)
  1 stk PRODUCTION PHASE (PP503PROD)
    100,6 kWh Dansk elproduktion, 1992, TERMINERET (L32719T98)
    9,18 kg Naturgas ved fyring <1MW (E32761)
    0,005 kg WATER BASED SOAP (K32800)
    0,08 kg UREA FORMALDEHYDE GLUE (K32801)
  1 stk DISTRIBUTION PHASE (PP503DIST)
    1 stk PACKAGING (PP5031700)
      1 stk PLASTIC BAG (PP5031710)
      1 stk CARDBOARD BOX (PP5031720)
    1 stk TRANSPORT (PP5031900)
      1400 kgkm Lastbil 3,5-16t diesel motv.TERMINERET  (O32696T98)
      4831 kgkm Lastbil, >16t diesel motorv.TERMINERET (O32693T98)
      5,171E4 kgkm Containerbåd, 2-t, 28000 DWT, TERMINERET (O32715T98
  1 stk USE PHASE (PP503USE)
    1E5 g Uspec. vand (R32649)
    0,05 kg Uspecifceret sæbe* (K32529)
  1 stk DISPOSAL PHASE (PP503DISP)
    0,26 kg Affaldsforbrænding, PE, TERMINERET (B32647T98)
    2,3 kg Affaldsforbrænding, pap, TERMINERET (B32638T98)
    4,65 kg INCINERATION, HARD WOOD (B32800)
    0,2 kg Affaldsforbrænding, PUR, TERMINERET (B32642T98)
    1,1 kg INCINERATION, PLYWOOD (B32801)
  1 stk MATERIALS (PP503MAT)
    4 stk LEG (PP5031100)
    1 stk FRONT SEAT RAIL (PP5031200)
    1 stk BACK SEAT RAIL (PP5031300)
    2 stk SIDE SEAT RAIL (PP5031400)
    1 stk SEAT (PP5031500)
      1 stk PLYWOOD SEAT (PP5031510)
      1 stk FOAM RUBBER SEAT (PP5031530)
      1 stk LEATHER UPHOLSTERY (PP5031540)
    1 stk ARMRAIL (PP5031600)
      2 stk ARMREST (PP5031610)
      1 stk BACK RAIL (PP5031620)
      830 kgkm Lastbil 3,5-16t diesel motv.TERMINERET  (O32696T98)
```

ID: PP5031000
Name: THE CHAIR'50
Type: Productsystem
Description: The model PP503 is a dining wooden chair designed in 1949 by Hans J. Wegner and produced by PP Møbler in soap-treated ash. The functional unit is providing a seat in which it is possible to seat comfortably for several hours, for at least 100 years.
Phase:
Key Unit: stk
Site:
Area:
Reference date: 27-05-99
Code no. (e.g. CAS no.):
Status: ○ Empty ● Not Done ○ Done
Date of Creation: 27-05-99
Date of Change: 16-06-99
User ID: IPU
Scenario: 0
0 Officiel IPU

Figure 7.13 Product model in the LCV-tool of the chair [Lucchetta 99]

The LCV-tool calculated a table with weighted data (such as table 7.5 in the previous example). These data are presented in **figure 7.13** separated into life cycle stages. Note that the Use stage is not mentioned because no processes occur here. For the comparison with OPM results, the mPET- values given below were summarised to a single figure for each life cycle stage.

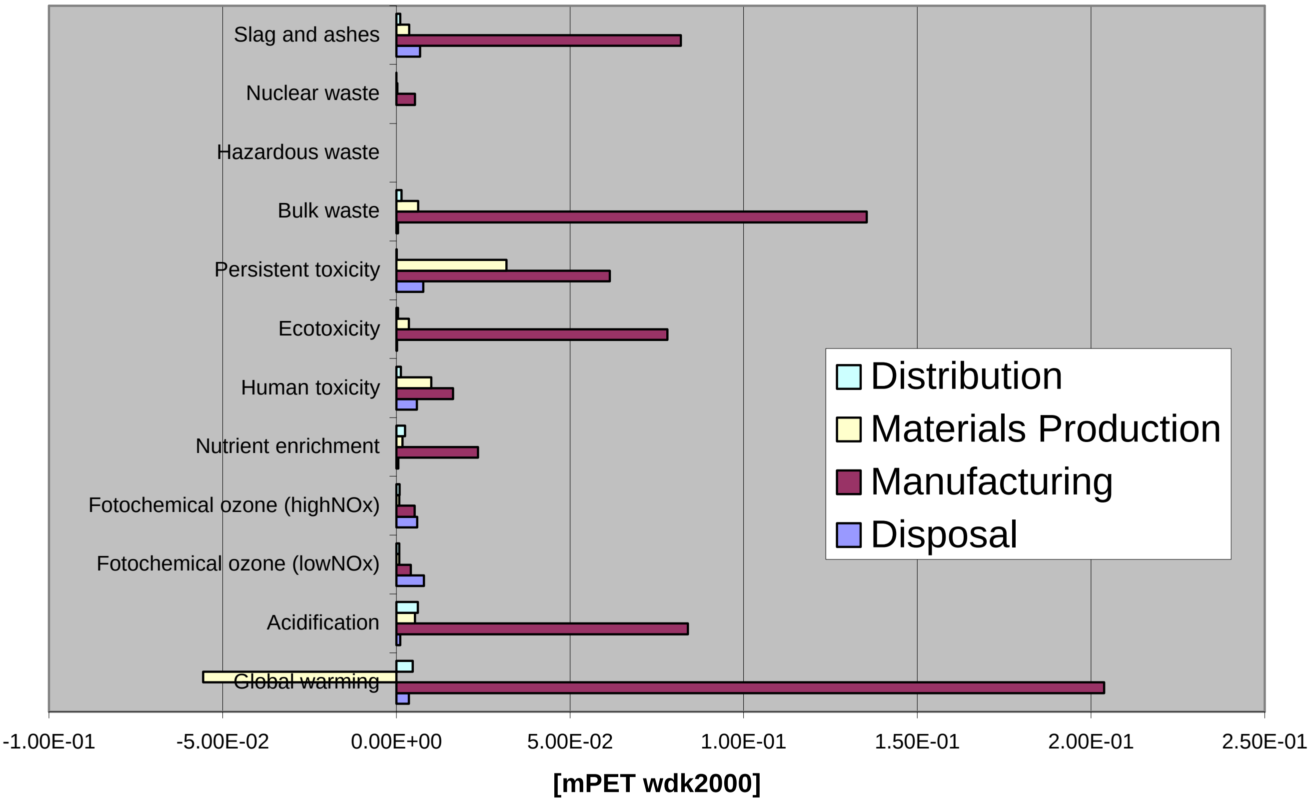


Figure 7.14 Weighted environmental impact potentials for the chair PP 503 (The negative contribution to Global Warming is based on the a product model which accounts wood negative in the Materials Production stage. The summed data used in the comparison are corrected for this problem.)

The Oil Point evaluation corresponding to the same product data but with an adjusted product model, is given on the next page.

Life cycle stage	Material or Process	Quantity	OP indicator	Result
Material	Ash timber	4.7 kg	0.1 OP/kg	0.5 OP
Production	Plywood	1.1 kg	0.2 OP/kg	0.2 OP
	PU foam	0.4 kg	1.2 OP/kg	0.5 OP
	Natural leather	0.2 kg	0.3 OP/kg	0.1 OP
	Glue	0.2 kg	0.9 OP/kg	0.2 OP
	PE (packaging)	0.3 kg	1.8 OP/kg	0.5 OP
	Cardboard (packaging)	1.2 kg	0.6 OP/kg	0.7 OP
			Sub total:	**2.7 OP**
Manufacturing	Sawing	7.5 m	0.1 OP/m	0.8 OP
	After-drying	0.03 m^3	20 OP/m^3	0.6 OP
	Machining	11.5 kg removed material	0.8 OP/kg removed material	9.2 OP
	Forming	0.3 m^2	0.2 OP/ m^2	0.1 OP
	(Overhead energy)			(23.5 OP)
			Sub total:	**10.7 OP** **(34.2 OP)**
All Transport	Transport to factory and to market	Truck, ship and train	…	0.6 OP
			Sub total:	**0.6 OP**
Use	(no processes)			
			Sub total:	**0 OP**
End-of-Life	Ash timber incineration	4.7 kg	-0.4 OP/kg	- 1.7 OP
NB:	Plywood incineration	1.1 kg	-0.4 OP/kg	- 0.4 OP
Calculation	PU foam incineration	0.4 kg	-0.4 OP/ kg	- 0.2 OP
principle changed	Leather incineration	0.2 kg	-0.2 OP/kg	- 0 OP
	Glue incineration	0.2 kg	-0.4 OP/kg	- 0.1 OP
	PE incineration	0.3 kg	-0.7 OP/kg	- 0.2 OP
	Cardboard incineration	1.2 kg	-0.3 OP/kg	- 0.4 OP
			Sub total:	**- 3.0 OP**
			TOTAL:	**11 OP**

Table 7.12 Evaluation of a chair using the Oil Point method (Data and calculation [Lucchetta 99], The value for overhead energy is mentioned for comparison only)
(REMARK: THE CALCULATION PRINCIPLE FOR END-OF-LIFE IS NOW CHANGED! SEE SECTION 6.7)

7.7.3 Summarised result and conclusions

The results obtained from the two evaluations are summarised in **figure 7.15** below.

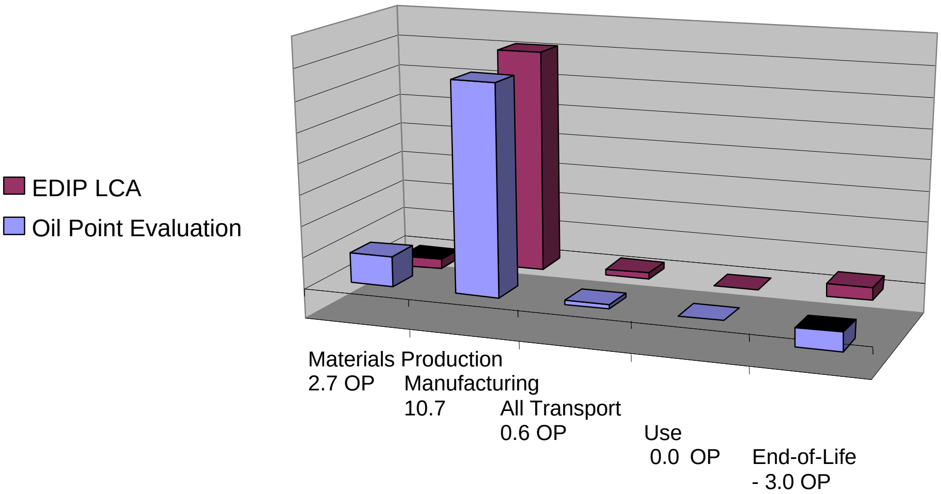


Figure 7.15 Comparison of evaluation results obtained by the OPM and by EDIP

The figure allows two main conclusions:

1. Both methods deliver a similar profile for this product
2. The manufacturing stage is the environmentally most problematic stage in the life cycle of this type of product

Three scenarios with product changes were calculated with the EDIP-tool as well. They comprised:

- Variation of life time (15, 50 and 100 years)
- Variation of seat material (model 501, cane vs. model 503, leather)
- Variation of surface treatment (lacquering vs. soap treatment)

A shortening of the life time resulted in direct proportional increase of mPET-values. This does not surprise as the chair does not have impacts in its Use stage and environmental impacts are calculated *per person and year* in LCA (see Chapter 3). The environmental impact of the Materials Production, Manufacturing, Transport and End-of-life stage is thus calculated as being distributed over the number of years of the life time, resulting in lower impact per year if the life time is increased. The simulated change of the seat material resulted in negligible reductions in overall impact potential, also due to the shorter life time of cane as the seat material.

A change of the surface treatment from soap to lacquer, however, resulted in significantly increased mPET-values, especially for Human toxicity and Persistent toxicity.

The overall mPET value for the lacquered chair became about five times as high as the one for the soap treated chair (ca. 0.65 mPET vs.

3.3 mPET). This last result could not have been detected by an Oil Point evaluation!

An overall conclusion is therefore that, in the group of passive products with a long lifetime the OPM *can* lead to the same result as a formal LCA, if influences from chemicals can be excluded. Taking the result of the previous case study on window frames into account, the OPM can be declared valid for both comparative and analytical evaluations of passive products only in cases where chemical influences can be neglected a priori.

7.8 Case 5: Two sweaters

Subject in this case are two sweaters: one made of 100 % polyethylene terephtalate (PET) fibres (commonly known as Polyester) and one made of 100 % cotton fibres. (The picture on the left is exemplary.) These textile garments are chosen as representatives for the group of hybrid products: They don't require any technical form of energy to fulfil their primary function, but do require it for processes to *maintain* the usability in the primary function, namely for the processes of washing and, maybe, tumble drying.

For this case study, some data of "UMIPTEX", a pre-project on LCA of textile products, have been utilised for the EDIP calculations (see [UMIPTEX 98]) together with data from a report from the Danish Environmental Protection Agency (DEPA) on environmental assessment of textiles [DEPA 97] and a report from the Danish National Consumer Agency [NCA 96] on family activities. Eco-indicators were derived from [Goedkoop 95b]. For the OPM-evaluation, Oil Point indicators were derived from the UMIPTEX energy data in order to provide the same data basis.

The main question to be answered is, again, whether the main conclusion to be drawn by means of the Oil Point Method is similar to those suggested by the other two more complex methods - especially with respect to a decision upon a preferable material. It is thus of interest, to what degree the results of the three methods correlate.

7.8.1 Product systems and Functional Unit

Both the polyester and the cotton sweater are both assumed to weigh 1 kg, and to require 3 kg fibre material. The use stage consists of 75 times washing and tumble-drying in Europe. In the end-of-life stage, 75 % of the sweaters are incinerated and 25 % disposed of by landfill.

The washing powder is only included in the EDIP-figures and not in the EI 95 figures, due to a missing Eco-indicator value.

A summary of the used inventory data is given in **table 7.13**. Water consumption is stated there for both alternatives just for informative reasons. It does not enter the evaluations as water consumption is not taken into account on any of them.

	Materials Production (incl. processing to fibres)	Manufacturing	Transport Weight: 1 kg	Use 75 x washing and tumble-drying, (e.g. every second week over ca. 3 years)	End-of-life 75 % incineration, 25 % landfill
PET sweater	• 3 kg PET granulate from crude oil,	• 2.6 kg fuel oil, • 0.2 kg gas oil for 5 manufacturing steps	• 0.8 tkm truck transport	• 18 kg fuel oil, • 1.5 kg washing powder, • 1.8 m^3 water during use	• calorific value 23 MJ/kg
Cotton sweater	• 100 g semen, • 3 kg cotton, • 4 kWh electricity • 0.7 kg fuel oil • 3.5 MJ unspecified primary energy • 4 m^3 water/ kg cotton • no colouring	• 13.6 kWh, • 0.9 kg fuel oil • 0.1 kg gas oil for 5 manufacturing steps	• 1.5 tkm truck transport	• 19.5 kg fuel oil, • 1.5 kg washing powder, • 1.8 m^3 water during use	• calorific value 12 MJ/kg

Table 7.13 The Inventory data used in all three evaluations of the two sweaters [UMIPTEX 98, DEPA 97]

The mentioned calorific values are from the LCV-tool which, again, was used for the EDIP evaluation. The Functional Unit is defined as: *“Provision of a clean, non-coloured knitted sweater of 1 kg weight, to be used, washed and tumble-dried 75 times in Europe.”*

7.8.2 Summarised result and conclusions

The results of the three evaluations are shown on the next page. (Eco-indicators for cotton production and cotton manufacturing are not given in [Goedkoop 95b]. To facilitate a comparison, the EI 95 result of the PET sweater is given as a sum of two parts.

	Sweaters					
	PET			Cotton		
	EDIP [mPET]	EI 95 [mp]	OPM [OP]	EDIP [mPET]	EI 95 [mp]	OPM [OP]
Material Production	9.7	22.8	2.4	4.1	**?**	1.8
Manufacturing	8.7	19	2.8	11.2	**?**	4
All Transport	0.1	0.3	0 *	0.2	0.6	0 *
Use	32.4	126.5	19.3	33.7	132.5	20.8
End-of-life	0.5	1.4	0.4	0.4	2.0	0.2
Total:	51.4	41.8 + 128.2	24.9	49.6	**?** + 135.1	26.8

Table 7.14 The results of the textile case
*: the value is just above zero

On the next page, the results from **table 7.14** are given as bar charts.

The EDIP results allow two instant conclusions:

1.) The use stage, i.e. washing and tumble drying, has the highest impact potential for both materials.

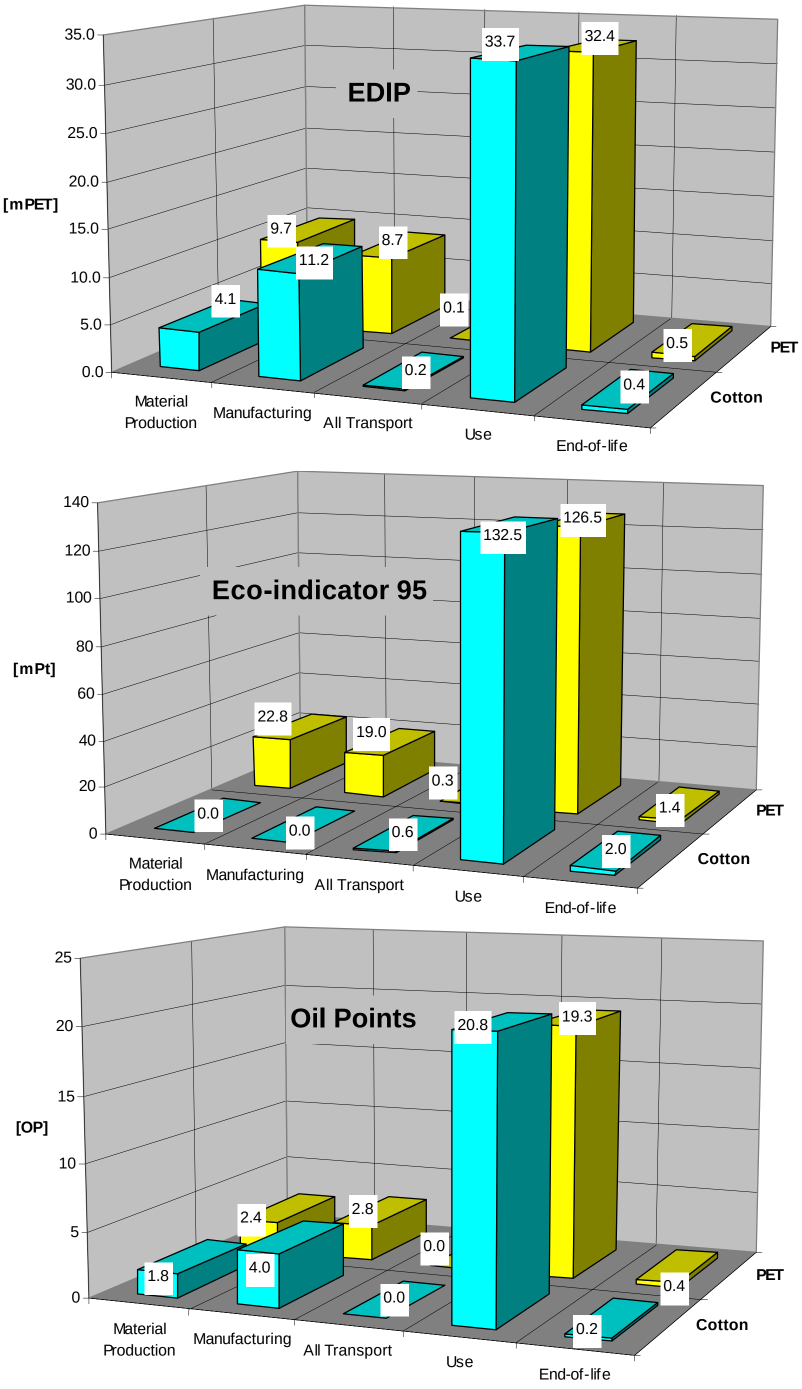
2) In the overall result, cotton performs slightly better than PET but the results are not significantly different from each other.

A report from the Danish National Consumer Agency [NCA 96], states that about 80 % of the energy consumption during use is required for tumble-drying, the rest for washing. Drying energy requirement is dependent on the amount of water absorbed by the fibres.

A conclusion could thus be to run simulations with surface-coated cotton fibres, which would absorb less water. Surface-coating, however, would also result in additional impacts in Materials Production and Manufacturing, (compare also [UMIPTEX 98]).

There are no Eco-indicators defined for cotton production or cotton manufacturing processes. An overall comparison of cotton and PET is thus impossible. However, the importance of the use stage for the EI 95 result is evident from the existing data.

The omission of washing powder is not significant for the comparative result because both alternatives are assumed to use the same amount (see table 7.13 again).



Similar to the preceding evaluations in this case study, the Oil Point evaluation stresses the importance of the use stage for textiles, even without taking washing powder into account. (Its inclusion would mean a similar increase of both OPM results respectively both EI 95 results) Although the material production of the PET sweater is based on non-renewable non-recycled material, the comparatively lower energy consumptions during manufacturing and use of this material are reasons for an overall slightly better performance of the PET sweater.

In the important use stage, cotton performs worse than PET in all three evaluations. This is probably due to the fact that the cotton fibres absorb more water which afterwards requires more energy for drying

Figure 7.16 Comparison of evaluation results obtained for two materials for sweaters by EDIP, EI 95 and OPM

The selection of a material which absorbs the smallest amount of water and/or the inclusion of a coating process would be an appropriate measure of product improvement here. Transport processes are practically unimportant in all evaluations.

While the total result of the EDIP evaluation is better for the cotton sweater than for the PET sweater, the result of the OPM evaluation is just the opposite. However, in both evaluations the results of both alternatives lie very close to each other. Comparing the single stages of the life cycle, the energy figures show exactly the same tendencies as the EDIP figures.

This indicates, that it is primarily the energy consumption which is responsible for the potential impacts in this example.

This indicates the validity of the OPM in this case. However, this indication has to be treated with caution because assumptions and modelling have a very strong influence in this case. A scenario without the energy-intensive tumble-drying and maybe with separated use- and wash-patterns for the different fibres (e.g. based on different dirt absorption, which could result in fewer washings) could probably lead to a very different picture. Also, most UMIPTEX data used, were non-specific literature data, which were meant to be exchanged by specific data in the course of the main UMIPTEX project, especially because textile industry is a chemicals-intensive industry.

All in all, the OPM is therefore not considered to be generally valid for hybrid products at this state of research. Additional case studies, e.g. on cutlery and pottery, are required here. The very character of hybrid products seems often to be determined by the fact that a “cleaning” process of some sort is involved. Cleaning processes, in turn, often involve hazardous substances. Therefore, the *ratio* between the importance of chemicals and the importance of energy requirements determines, whether the OPM is valid or not. In the Sweater case, this ratio seems to be dominated by energy requirements.

7.9 Conclusions

In this chapter, a cross-check of results obtained by means of the Oil Point Method with results from two other established methods with higher degree of complexity was made. In this way, the Oil Point Method should be validated.

As results always depend on the model, the data and the method used, the cases were conducted with same models and same data, wherever possible. In the EDIP and the Eco-indicator method, data are supplied in the form of “unit processes” respectively “Eco-indicators”. What was *not* done, is a detailed cross-check of the actual data included in these unit processes and Eco-indicators (both are, however, documented in the LCV-tool [EDIP 98] respectively in “The final report” of the Eco-indicator 95 [Goedkoop 95a]). It is, however, assumed that the deviations in background data are generally small as both tools are developed by professional experts in the field. Spot checks of data supported this assumption.

The cross-checking was performed for several product groups.

An overview of cases, results and conclusion with respect to validity of the OPM for the product categories is given in **table 7.15**.

Product type	Case	Validity of OPM in case			Overall validity	Recommended action
		Yes	No	In doubt		
Active	1. Coffee machine	**X**			**Yes**	**Use OPM**
	2. Vacuum cleaner	**X**				
Passive	3. Window frames	**X**			**Not in general**	**Cross-check with other method**
	4. A chair			**X**		
Hybrid	5. Sweaters			**X**	**Not in general**	**Cross-check with other method**

Table 7.15 Overview over case studies and conclusions for validity of the OPM

Oil Point evaluations are sufficient under the condition that energy-related impacts are dominant in the life cycle of a product. The case studies showed that this *is* the case for active products and *can be* the case for hybrid products and even for passive products.

Deducing from the two first cases, the OPM can be generally applied for active products, such as coffee machines and other electro-mechanical consumer products. For sporadically used active products, such as vacuum cleaners or electric drilling machines, materials selection can be relevant for the overall environmental performance but the usually long life time makes energy consumption during use still the dominant factor. A cross-check with an LCA method is, thus, not seen as necessary for active products.

As regards, passive products, one case indicated validity another some doubts. It is therefore not excluded to use the OPM, as chemical substances not necessarily occur during the life cycle. A cross-check with another LCA method can be recommended.

The case on the hybrid product showed that the OPM may well be applicable on this kind of products, but only, if chemical substances are not dominant over the energy-related impacts. However, as chemicals are very likely to occur during the use stage (e.g. in the form of cleaning agents), it is highly recommended to cross-check results for hybrid products with another method.

As none of the five cases indicated a decided non-validity of the OPM and as energy-related impacts generally were of high importance, also in the doubtful cases, the OPM is considered to be a valuable tool for rough environmental evaluations.

8 Critical Evaluation

This chapter is dedicated to a critical discussion and evaluation of the assertions and findings stated in this thesis. Specifically, this will be done for the method itself, for the disregard of chemicals in the OPM and in comparison with other indicator-based methods. The procedure of dealing with the research problem will also be discussed.

Overall conclusions to be drawn from the results and suggestions for further work are subject of the subsequent chapter.

8.1 Summary of the thesis

After the introductory chapter, the term “Environment” and the overall environmental context were discussed in Chapter 2. Fundamentals of Environmental Assessment were described in Chapter 3, while Chapter 4 gave an overview over Materials and Process Selection as a discipline within Product Development. Current approaches on how to integrate and treat “Environment” in Design and Product Development were reviewed in Chapter 5 including work that has been done in the field of Environmental Materials and Process Selection itself. The Oil Point Method, which has been developed to meet the requirements of this context, was explained in Chapter 6, followed by five comprehensive comparative or analytical case studies in Chapter 7.

8.2 The Oil Point Method as such

The overall aim of the OPM is to produce a result, which indicates actual related environmental impact and which thereby provides a proper basis for the selection process at a conceptual level.

Concerning the Oil Point Method as such it is of interest, whether or not it fulfils the requirements stated in the beginning of the thesis. These requirements were determined in Chapters 3, 4 and 5. The general requirements can be summarised as follows:

1. The method should be relatively easy to learn and to apply in practice (e.g. by founding on basic insight into environmental correlations and by requiring relatively little time in application),

2. It should give quantitative results (i.e. appropriate for designers and for the selection problem)

3. It should indicate the approximate size of the main environmental consequence, which is connected to a selection, as well as the location of this in the product life cycle

4. It should minimise the problem of missing data that occurs when indicator values for a certain material or life cycle process are missing

Requirements 2 and 3 can be stated to have been met. The method gives full-quantitative results and problematic life cycle stages can be determined, as has been shown in the case studies. It was also shown that by means of the Oil Point Method design options could be tested against each other.

Whether or not the method is easy to learn (requirement 1) has not been verified specifically. However, the method was introduced and discussed on a dedicated seminar with 15 designers and LCA specialists and on several Life Cycle Design-oriented conferences and workshops. Result from discussions on these occasions is that the OPM is applicable in the same straight-forward way as other indicator-based evaluation methods. The appropriateness of such simplified methods for designers had, for instance, been pointed out by Dutch and British empirical research [Bakker 95, McAloone 98]. Focus in the Dutch project had been industrial designers and their requirements with respect to environmental information. The British investigation focused on electric/electronics industry in the UK and the USA. Both concluded with the request for simplified methods in Life Cycle Design.

Concerning requirement 4, it has not been investigated whether the principle of using energy data actually leads to minimised problems with retrieval of missing data. However, first of all, the compiled list of Oil Point indicators covers a wide range of material and process types. It is assumed that the provided range is useful in most early design situations. If a specific material is to be evaluated, e.g. a certain composite material, contacting manufacturers is an option. Getting energy data that way today is more likely than it used to be earlier due to the generally increased focus on environmental issues in companies and society. Estimating Oil Point indicators based on existing ones is also possible. The Internet as publicly accessible source for energy data is obvious as well. Recently, for instance, the Association of Plastics Manufacturers in Europe (APME), which has been used as a data source during this research, made their renowned reports on various polymers etc. available on the Internet (under: lca.apme.org). All in all, the basic requirements upon the OPM have, thus, been met or can be expected to be met in design practice.

Characteristics of the OPM can be summarised as follows, (including related chapters, **table 8.1**):

Characteristic	Chapter	OPM
1. Rough calculations, easy to learn & apply	5	YES
2. Quantitative results	3, 4	YES
3. Absolute data-based, thus indicating the approximate *absolute* consequence	5	YES
4. Minimised "missing data problem"	5	YES
5. Life cycle approach-based	3	YES
6. Functional Unit-based	3	YES
7. Usable by individual designers	5	YES
8. Supports idea generation	*5*	*NO*
9. Usable on all product groups	*5, 7*	*NO*
10. Gives a complete environmental picture	*2, 3*	*NO*

Table 8.1 Characteristics of the Oil Point Method and related chapters

One more self-critical comment on the OPM as such: When reading Chapter 6, where the method is described, one cannot avoid asking: "Is this really a *simple* method?" The author's answer is "Yes, applying the method is relatively straight-forward. However, environmental evaluation requires an understanding of some crucial elements, e.g. the basis on a functional unit and the life cycle concept, and the methodological choices such as the disregard of chemicals have to be stated clearly in order to make the method transparent towards the user".

A "one page" description of the three steps in the OPM is, however, provided in Appendix II.

8.3 Disregard of chemicals and attempt to separate product groups

A main matter of investigation, documented in the five case studies, was to find out for which product groups the OPM is applicable and for which not. The OPM exclusively uses primary fossil energy relations to quantify environmental impact. The exclusion of hazardous substances, representing another important source of environmental impact, had to be addressed. It was, therefore, tried to determine product groups where chemicals on average had a minor influence and where energy, thus, was a valid parameter to be used stand alone.

This was done by assessing the same product system with three different methods.

In cases where the results of the OPM would have been strongly deviating from the other results, chemicals were likely to be responsible and important. The case studies in Chapter 7 indicated, not surprisingly, that using energy as main parameter and thus using the OPM is generally valid for electricity-consuming “active” products, both for those used frequently and those used occasionally.

For the evaluation of “passive” and “hybrid” products, the conclusion was to make a crosscheck with a method that includes chemical aspects.

After the cases had been concluded, an approach to cope with chemicals in the OPM was made. The 62 products and (ancillary) materials that were included on the “List of undesirable substances” of the Danish EPA were compiled, see App. III (the original list is ordered after substance, not material or product). The new list provides answers to two central questions a designer might have:

- “Is ‘my’ material or product on that list, i.e. potentially harmful?” and, if yes
- “Why is it on the list?”

“Plastics” are for example on the list because they may contain brominated flame retarders. The designer can then decide, whether this may be a relevant issue for the design at hand. Paints & varnishes, cosmetics, adhesives, coolants/Lubricants and textiles are on the list as well.

A clear statement that the OPM in any of the cases indicated significantly different results compared to LCA results could not be made. The OPM is, therefore, generally applicable for all kinds of industrial consumer products. Industries generally covered include automotive, shipbuilding, machine tools/tools & dies, (non-paper-based) packaging, glass, white goods. Specifically excluded are chemical-intensive industries such as paper, textile and food.

8.4 Delimitation against other methods

Eco-indicator 95, EPS

The Dutch Eco-indicator 95, the Swedish EPS (Environmental Priorities Strategy) and the Oil Point Method are similar in so far, as they are all intended to be used by designers (not necessarily environmental specialists) and their application is indicator-based. An indicator indicates e.g. “environmental load per mass of material”. The main difference of the OPM compared with these methods is the reduction of problems related to missing data. As soon as e.g. an Eco-indicator for a certain material is missing, the designer either has to require this from somewhere or has to calculate with a value for another material. An estimation of the value is not appropriate because Eco-indicators are aggregated values, e.g. resulting from Cradle-to-gate inventories. This problem is substantially minimised in the OPM, as explained in section 9.1.

CED

Cumulated Energy Demand (CED, German: KEA) and Oil Point Method have the similarity in the concept of accounting primary fossil energy, see section 3.7.4 and e.g. [CED 97]. The CED approach, however, is a very detailed one intended to be used, for instance, within LCA. CED values are no indicators either.

In contrast to that is the OPM deliberately simple also in the calculation of the indicators. The Cumulated Energy Demand represents a “microscopic” approach while OPM is a dedicated “macroscopic” approach. The CED approach is based on calculations, which are very detailed for the different life cycle stages and, which denote the ambition to be scientifically “exact”. With the OPM, however, the ambition is (only) to be “exact/correct” in orders of magnitude, as needed in early design. Another important difference between KEA and OPM is the target group: While KEA generally addresses engineers, the OPM is also directed towards non-engineers.

Guidelines

A third alternative are guidelines. They give direct support to *idea generation.* Examples are guidelines such as “Use recyclable (or even better: recycled) materials”, “Use low-weight materials” or “Use energy conserving manufacturing processes”. Guidelines are indeed a useful means to make designers think in certain directions. However, they have two major disadvantages: Firstly, they very often lead to contradictions (in the examples named above: What about a low-weight material, which cannot be recycled easily (such as composites)?). Secondly, guidelines do not enable the designer to choose the best solution of a set of options because they are not quantitative. In a situation where a solution has been developed according to each of the three guidelines named above, the designer would thus not be able to determine, which of the three would be preferable; with a quantitative method, such as the OPM, he or she could. A useful form of guidelines are, however, product family guidelines, as they can refer to the product type the designer works on.

8.5 Procedure of solving the research problem

The research problem addressed in this thesis was how environmental regard could best be integrated into materials-related decision-making processes of environmentally non-specialised designers. This meant working in a relatively broad field of research.

Following an analysis of the situation in both materials & process selection, in design & product development and in environmental evaluation, a new method to cope with the problem in the very early stages of product development was developed. This method was validated by means of case studies with examples from environmentally distinctive product groups.

However, the method was, not tested empirically. Although it was presented and discussed on workshops, seminars and conferences, the (ultimate) validation by professional designers was not made.

9 Conclusions and Suggested Next Steps

9.1 Conclusions

The intention with this research project was to support environmental decision-making in materials and process selection, early in the product development process. Reflecting on how to do this based on current state-of-the-art in environmental assessment, one realisation was made soon: environmental materials and process selection has to be done in a life cycle perspective of the product.

As was shown in Chapter 5, existing methods for that task don’t always consider this crucial requirement. In fact, all methods analysed showed some more or less decisive drawbacks. Only one of four methods developed or recommended for materials selection incorporated Functional Units as the basis for comparisons. This alone is reason enough to look for better methodological ways in environmental materials and process selection.

Taking other requirements into account, such as the applicability by non-environmental specialists and the need for quantitative results that enable direct comparisons of alternatives, the development of a new method seems fully justified.

But what about the outcome? Comparing characteristics of the Oil Point Method with those of competing methods speaks clearly for this new method. From the point of view of environmental assessment its application is also justified without doubt for “active” products. The main problem in the method is, however, that whenever chemical aspects cannot be excluded, its utilisation becomes ambiguous. This is a weak point of the OPM. However, even in the ambiguous cases with “passive” and “hybrid” products the OPM did not necessarily lead to wrong decisions.

The key question to be answered by the case studies were: “How far away from the ultimate full LCA result are results of the OPM? Can they be completely wrong?” and “For which product groups would it be sufficient to use the OPM, i.e. in which product groups are hazardous substances typically of minor importance compared to energy?”

The “List of undesirable substances” by the Danish EPA (see App. III) gives a clear hint: it lists many ancillary substances and only some products where materials selection could play a role.

Two of the products of the latter kind were actually in the case studies: Window frames (made of PVC respectively of impregnated wood) and textiles. It might therefore be assumed that in product groups, which are *not* mentioned on the “List of undesirable substances” the OPM could be used. The “safer” way, however, is to say that at least for all product and material groups mentioned on the list the OPM is not applicable, due to the mere existence of an undesired substance.

In most of the product groups, however, materials selection is no issue, as they don’t involve mechanical design. “Cosmetics” and “detergents” are examples for this. Products of the type “coolants/lubricants” or “soldering fluxes”, however, play a role in manufacturing, which may well be important for the environmental performance of the product. In the case with the chair, manufacturing was actually the most important life cycle stage.

All in all it can be concluded that the OPM exhibits a number of relevant advantages over other methods concerning its application. The OPM is relatively easy to use, gives quantitative results (which are needed for comparisons) and it minimises the problem of missing data by using data that are relatively easy to access or that can be estimates.

Concerning the quality of the results from the environmental point of view it can only be stated that using the OPM is never meaningless. In some cases (e.g. active products) it shows almost the same results as an LCA, and in ambiguous cases it shows at least a part of the problem. For the designer, these ambiguous cases can be detected, for instance by means of lists like the one from the Danish EPA. However, in order to come to a quantitative result in these ambiguous cases, an LCA is inevitable.

The overall conclusion from the cases and the comparison with existing methods for environmental evaluation is positive: The OPM seems to be a useful tool to support designers in early design of mechanical products. It appreciates many requirements from designers and it indicates at least the approximate minimum size of environmental implications related to products, which are subject to mechanical design.

9.2 Contribution of this research

This research provides the following contributions to the research field:

- An analysis of the current research in environmental evaluation and in environmental product development
- A classification of tools and methods for environmental assessment and design
- The identification of missing links between methods for environmental evaluation and their application in materials selection and product development procedures
- The development of a method, the Oil Point Method (OPM), which supports the selection of engineering materials and manufacturing processes with respect to minimised environmental damage
- The validation of the method by means of five case studies from major product groups

Furthermore, a set of data is established to apply the method with over 70 materials in pure or semi-finished form, over 20 manufacturing processes and some 30 other life cycle processes.

9.3 Suggested Next Steps

In a research work such as the one presented in this thesis, there are always “open ends” that are worth addressing. (From the experience of the author, it is even true that during research, when answering questions or explaining phenomena, one often reveals more open issues than one originally started off with). The most important open issues in this research work shall be suggested as subject for further work.

Concrete steps for further research could be:

- **Integration of chemical aspects** The current uncertainty in the OPM concerning influences of hazardous substances in concrete cases is unsatisfactory.

  A *qualitative* integration could be accomplished by integrating matrix-methods, such as the MECO matrix, and the OPM. Lists such as the “list of undesirable substances” could provide the information about whether or not a material or process involves hazardous substances

  A *quantitative* integration could be done, for instance, by means of an ABCDE categorisation of materials suggested by Nissen et al. [97] for electronics components. This categorisation could be transformed to figures 1-6, which could then be used as multiplication factors for energy values: A very toxic material would get a proportionally higher (modified) Oil Point indicator.

- **Resource aspects** are included in so far, as energy today is fossil fuel-based and fossil fuels are resources. A minimisation of life cycle energy consumption is under current circumstances, thus, also a minimisation of resource consumption. However, aspects like scarcity of metals could be integrated, either as a separate or an extended indicator

- Quantitative integration of material parameters such as **recyclability** and product structure parameters such as maintenance, **dis-assemblability**, etc , see e.g. [Wimmer 99]

- Extension of the number of indicators for **use and compound use processes.** In relation to their importance in the life cycle of many products, they are covered all too imprecisely by existing use indicators such as "electricity consumption". It is also very likely that, for instance, industrial designers will have difficulties in defining such processes on their own. Help in the form of indicators for processes such as "using a refrigerator in an average 4 person household" should be provided for selected product groups.

- Definition of Oil Point indicators for **standard sub-assemblies** (e.g. for "1 cm^2 printed circuit board")

- Definition Oil Point indicators of materials respectively manufactured materials according to **design properties**, i.e. "with adjectives". E.g.: "Transparent plastic", "Smooth-surface metal", "Shiny-surface metal", "magnetic material", etc.

In addition to that, the research procedure discussed in section 9.5 could have included two more steps:

- a broader empirical testing of the method's applicability in practice by designers and, in combination with that,

- the implementation of method and data in a publicly available tool, e.g. on the Internet.

As stated in section 9.1, the OPM has been presented at several seminars, colloquia and conferences. A specific empirical analysis, however, was not performed. Such an investigation would be a valuable source for detailed knowledge about the applicability of this particular method in practice and for identifying improvement potentials.

Both empirical testing and implementation on the Internet (see [Lenau 96-00]) are subject of a planned project.

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Appendix

Appendix I Oil Point indicators

The Oil Point indicators listed here are a compilation based on data from several sources. The indicators are grouped according to life cycle stages, i.e.

a) Materials,

b) Manufacturing,

c) Transport,

d) Use and

e) End-of-life.

Under d) some “Compound use processes” are mentioned, such as “*Use of a hair dryer over a year*”.

In general, Oil Point indicators are given with only one decimal, e.g. 1.6 OP/kg for Stainless steels. In the first place, this is done in order to keep calculations simple. It is, however, also done in order to avoid the impression of precision where it, per se, can’t exist as energy values can vary widely. Therefore, the range of values, or the single one from which an Oil Point indicator was derived is stated as well.

Exceptions are life cycle processes where large quantities are likely to be required for one product. For these processes, two decimals are given, e.g. 0.25 OP/kWh for electricity and 0.07 OP/kg for sandstone. Transport is also an exception.

OP indicators for materials: Fuel energy and sometimes also feedstock energy

All materials require “fuel energy” to extract them from Earth and process them into raw material. Materials based on fossil fuels, e.g. conventional plastics, as well as naturally grown materials, e.g. wood, contain additional energy, the so-called “feedstock energy”. While fuel energy is not recoverable, feedstock energy is recoverable, e.g. by incinerating the material. The sum of fuel energy and feedstock energy is called “total energy content of a material”.

Oil Point indicators for materials represent the total energy content expressed as Oil Points per kilogram of the respective material (OP/kg). The total energy content and, thus, also Oil Point indicators, are usually given for the material in its raw form. For cast iron, this raw form would be a slab of iron (i.e. a solid block), for plastics it would be the resin or a granule. Where the semi-finished form is given in the sources, e.g. a bar of Aluminium, this is indicated as a comment.

For materials, which contain a feedstock share, always two OP indicators are given: One for the fuel share and one for the feedstock share. This separation is necessary for Oil Point calculations in the stages “Materials production” and “End-of-life” (see Chapter 6). The polymer “Low density polyethylene (LDPE), for instance, has a fuel OP indicator of 0.9 OP/kg and a feedstock OP indicator of 1.1 OP/kg. The fuel OP indicator shows that a little less than one kilogram oil is required to produce one kilogram LDPE resin from crude oil. The feedstock OP indicator shows that a kilogram of LDPE resin contains a little more energy than one kilogram of crude oil does.

There are materials, for which any categorisation is ambiguous: Many textile fibres, for instance, belong to both “polymers” and “fibres”, wood is both a “natural material” and a “fuel”. In order to prevent the user from having to find the “right” category, it was decided to mention such materials under all respective categories. Thus, some redundancies in the list do occur.

OP indicators for processes: Only fuel energy

Processes of manufacturing, transport and use require fuel energy. “Fuel” can be supplied in the form of electric energy, gasoline respectively other liquid fuels or hard fuels, such as coal or wood. The OP indicators given for processes represent the total primary energy required to run these processes. For electricity consumption, an efficiency factor of 33 % has been included in the OP indicators.

The OP indicators for manufacturing processes include 33 % efficiency but do not include overhead energy, i.e. energy for heating, lighting etc. This can well be 50…75 % of all energy consumption for manufacturing. For typical manufacturing companies, the OP sum of the manufacturing stage can, thus, be doubled or tripled in order to include overhead energy requirements.

Main sources were:

(a) Four-volume student manual on manufacturing processes [Allen/Alting 86]
(b) Reports of Association of Plastics Manufacturers in Europe [APME 97-00]
(c) Book on Energy Analysis [Boustead/Hancock 79]
(d) Boustead ‘Model 4’ database [Boustead 98]
(e) BUWAL reports [BUWAL 96 a/b]
(f) “Energy Content”-values from Cambridge Materials Selector software [CMS 97]
(g) EDIP LCV-tool [EDIP 98]
(h) “Gross Energy Requirement(GER)”-values from IdeMat 98 database [Idemat 98]

Other sources were:

- Reports from the Danish Environmental Protection Agency [DEPA 96, 97, 98a]
- the UMIPTEX database [UMIPTEX 98]
- Master’s project reports [Liechti/Nyborg 98, Hermannsen 99, Lucchetta 99]

a) Materials Production

This section contains 72 Oil Point indicators for materials:

1. Metals,
2. Polymers,
3. Ceramics & glasses,
4. Composites,
5. Natural materials,
6. Fibres and
7. Other materials

1. Metals	**OP indicator**		**Total energy requirement**		**Comment**
			Typical [MJ/kg]	In the sources [MJ/kg]	Estimates are indicated by an asterisk-sign: * , extreme values and their sources by *italics*
Cast Irons	**0.6**	**OP/kg**	25	16…66	(c, f, g, h)
Carbon Steels	**1**	**OP/kg**	45	30…72	(f, h)
Steel (89% primary)	**0.9**	**OP/kg**	40	34…52	(c, g)
Steel plate (90% secondary)	**0.4**	**OP/kg**	18	16…18	(c, g)
Stainless Steels	**1.6**	**OP/kg**	70	*46*…115	(c, f, *g*, h)
Aluminium alloys, cast	**4.2**	**OP/kg**	190	142…335	(f, h)
Aluminium alloys, wrought or cast	**4.4**	**OP/kg**	198	155…335	(f, h)
Aluminium bar	**4.1**	**OP/kg**	183	183	(e)
Aluminium foil	**4**	**OP/kg**	181	170…193	(e, g)
Aluminium (100 % primary)	**4.4**	**OP/kg**	199	148…260	(c, e, h)
Aluminium (50 % secondary)	**2.1**	**OP/kg**	96	96	(e)
Aluminium (100 % secondary)	**0.2**	**OP/kg**	8	8…10	(c, e, g, h)
Copper alloys, brass	**1.8**	**OP/kg**	80	57…120	(f, g, h)
Copper alloys, bronze	**2.5**	**OP/kg**	113	110…120	(f, h)
Copper cable	**2.3**	**OP/kg**	102	102	(g) lacquered, for electronics, On DEPA list
Nickel, pure	**4.4**	**OP/kg**	200*	150…360	(f, g, h) for plating
Zinc alloys	**2**	**OP/kg**	90*	53…145	(f), (h)
Zinc (100% primary)	**1.6**	**OP/kg**	70	50…85	(f), (g) 100% primary
Magnesium alloys	**8.9**	**OP/kg**	400*	212…490	(f, h), [Euromat 98]
Titanium alloys	**22.2**	**OP/kg**	1000*	575…1300	(f, h), [Euromat 98]
Metal powders	**15.6**	**OP/kg**	700	400…1000	(f)

2. Polymers	**OP indicators**			**Energy content**		**Comment: as resin, for fibres see 6.**
	Fuel share [OP/kg]	Feedstock share [OP/kg]	Total	APME data total (fuel/feedstock) [MJ/kg]	Other sources, total [MJ/kg]	Estimates are indicated by an asterisk-sign: *
HDPE	**0.7**	**1.1**	1.8 OP/kg	82 (33/48)	81…120	(b, e, f, g, h)
LDPE	**0.9**	**1.1**	2 OP/kg	90 (41/48)	75…110	(b, e, f, g, h)
Polypropylene, PP	**0.7**	**1.1**	1.8 OP/kg	81 (32/48)	74…110	(b, e, f, g, h)
Polystyrene, PS	**0.7**	**1.6**	2.3 OP/kg	102 (30/72)	96…104	(b, e, f, g, h)
Expandable PS	**0.8**	**1.1**	1.9 OP/kg	84 (35/48)	84…96	(b, e)
Polyvinyl chloride, PVC (hard)	**0.8**	**0.7**	1.5 OP/kg	66 (34/31)	57…106	(b, e, f, g, h) on DEPA list
Polyamide, PA: (Nylon)	**2.8**	**0.7**	3.5 OP/kg	156 (127/29) (g)	156…180	(f, g, h)
Nylon 66	**2.1**	**1.1**	3.2 OP/kg	144 (95/49)	-	(b)
PET resin	**0.8**	**0.9**	1.7 OP/kg	77 (38/39)	77…86	(b, e, f, g, h)
PET film	**1.5**	**0.9**	2.4 OP/kg	110 (71/39)	-	(b)
Epoxies, EP	**2.2**	**1.1**	3.3 OP/kg	150 (100/50)*	100…199	(f, h) on DEPA list
Polybutadiene (Synthetic rubber)	**0.8**	**1.2**	2 OP/kg	90 (36/54)*	84…150	(b, c, f, g, h)
ABS	**1.1**	**1**	2.1 OP/kg	95 (49/46)	85…120	(b, f, g, h)
PU, flexible	**1.5**	**0.7**	2.2 OP/kg	100 (70/30)*	90…106	(f, h)
PC	**1.8**	**0.8**	2.6 OP/kg	116 (78/38)	95…206	(b, f, g, h)
PMMA	**1.5**	**0.9**	2.4 OP/kg	110 (70/40)*	100…120	(f)

3. Ceramics, Glasses, Non-metallic minerals	OP indicator		Total energy requirement		Comment
			Typical [MJ/kg]	In the sources [MJ/kg]	Estimates are indicated by an asterisk-sign: *
Cement	**0.1**	**OP/kg**	5	4…9	(f)
Concrete	**0.1**	**OP/kg**	3	1…5	(f, h)
Brick	**0.1**	**OP/kg**	5	2…10	(f)
Glass for bottles	**0.3**	**OP/kg**	13	10…25	(e, f g)
Glass for bottles (100 % secondary)	**0.2**	**OP/kg**	6.6	6.6	(g)
Porcelain	**0.1**	**OP/kg**	4	2…6	(f, h)
Technical ceramics	**4.4**	**OP/kg**	200*	50…300	(f, h)

4. Composites	OP indicator		Total energy requirement		Comment
			Typical [MJ/kg]	In the sources [MJ/kg]	Estimates are indicated by an asterisk-sign: *
GFRP	**2.2**	**OP/kg**	100	60…150	(f, h) Glass fibre-reinforced polymer (e.g. epoxy)
CFRP	**11.1**	**OP/kg**	500*	300…700	(f) Carbon fibre-reinforced polymer (e.g. epoxy)
Particle board (e.g. MDF)	**0.2**	**OP/kg**	10*	6..20	(f), [Bey 95], compare Table 5: Natural materials
Wood chips	**0.8**	**OP/kg**	-	35 (16/19)	(e), compare Table 5: Natural materials
Laminate polymer/metal	**1.9**	**OP/kg**	86	86	(h)
Metal Matrix Composites (MMC)	**15.6**	**OP/kg**	700*	400…1000	(f) Incl. metal powder

5. Natural materials	**OP indicators**			**Energy content**			**Comments**
	Fuel [OP/kg]	Feedstock [OP/kg]	Total	Fuel [MJ/kg]	Feedstock [MJ/kg]	total [MJ/kg]	Estimates are indicated by an asterisk-sign: *, chosen values in **bold** type
Wood, all kinds incl. bamboo	**0.2***	**0.3***	0.5 OP/kg	2…**8**	**15**…18	17…46	(f, g, h), [Wegst 96], *Methane generation when landfilled!*
Hemp, Flax	**?**	**?**	0.1 OP/kg			4..**5**..8	(f)
Sandstone	**-**	**-**	**0.07 OP/kg**	-	-	2..**3** 4	(f)
Leather	**?**	**?**	0.7 OP/kg	-	-	10..**30**..43	(f, h)

Impregnated wood is on the DEPA list of App. III

6. Fibres	**OP indicators**			**Energy content**			**Comments**
	Fuel [OP/kg]	Feedstock [OP/kg]	Total	Fuel [MJ/kg]	Feedstock [MJ/kg]	total [MJ/kg]	Estimates are indicated by an asterisk-sign: *, chosen values in **bold** type
Glass fibres	-	-	**0.6 OP/kg**	-	-	10..**25**..34	(f, h), [Liechti/ Nyborg 98]
Carbon fibres	-	-	**7.9 OP/kg**	-	-	100..**355**..448	(f, h), [Liechti/ Nyborg 98]
Aramid fibres			**4.2 OP/kg**			191	(h)
Natural fibres:	*Absorb relatively high amounts of water during washing, thus less easy to dry*						
Cotton fibres	(0.6) **1.1**	(0.1) **0.1***	(0.7 OP/kg) 1.2 OP/kg	-	-	4…**53**	(f, h), [UMIPTEX 98] *(fuel: 1.1 OP/kg [Van Winkle et al. 78], p.281 in [DEPA 97], p. 46)*
Wool fibres			**0.2 OP/kg**			6..**8**..10	(f), [DEPA 97]
Viscose fibres	**0.8**	**0.3**	1.1 OP/kg			48	[DEPA 97] (assumed feedstock of 13 MJ/kg)
Silk fibres			**0.2 OP/kg**			6..**8**..10	(f)
Hemp fibres			**0.1 OP/kg**			4..**5**..8	(f)
Flax fibres			**0.1 OP/kg**			4..**5**..8	(f)
Man-made synthetic fibres:	*Absorb relatively small amounts of water during washing, thus easier to dry*						
Polyester (PET) fibres	**1.3**	**0.9**	2.2 OP/kg	**59***	23..**39***..50	**98**…109	(g, h), [DEPA 97] feedstock value from [APME 98], table 6 (PET film), Total of 2.2 OP/kg from [Idemat 98] (PET fibre)
Polyamide (Nylon)	**2.1**	**1.1**	3.2 OP/kg				PA 66
Acrylic fibres	**0.9**	**1**	1.9 OP/kg	41	45	**86**…157	(b), [DEPA 97]

Textiles are on the DEPA list of App. III

7. Other materials	**OP indicators**			**Energy content**			**Comments**
	Fuel [OP/kg]	Feedstock [OP/kg]	Total	Fuel [MJ/kg]	Feedstock [MJ/kg]	Total [MJ/kg]	Estimates are indicated by an asterisk-sign: *, chosen values are in **bold** type
Paper	**0.45**	**0.45**	0.9 OP/kg	21	21	22…55	(e, f) for newspapers *Involves chemicals!*
Cardboard	**0.4**	**0.4**	0.8 OP/kg	19	19	38	(e) (g: 9 MJ/kg 100% recycled)
Rubber	**0.8**	**1.2**	2 OP/kg	21..**36**..54	46..**54**..63	80..**90**..150	(b, c, f, g, h) Polybutadiene i.e. artificial rubber
Cement	**-**	-	**0.11 OP/kg**	-	-	4..**5**..9	(f)
Concrete	-	-	**0.07 OP/kg**	-	-	1..**3**..5	(f, h)
Brick			**0.11 OP/kg**	-	-	2..**5**..10	(f)
Responsive “smart” materials							See polymers respectively metals

Paints and varnishes are on the DEPA list of App. III

b) Manufacturing Processes

This section with 23 Oil Point indicators for manufacturing processes is divided into

1. Mechanical mass reducing processes,
2. Metal forming processes,
3. Casting & moulding processes,
4. Surface treating processes and
5. Other manufacturing processes.

1. Mechanical, mass reducing	**OP indicator**		**Total energy requirement**		**Comment**
			Typical [MJ/kg]	In the sources [MJ/kg]	
Machining, drilling, turning of metals	**0.4**	**OP/kg removed**	20*	0.5…37	(a, g)
Grinding of metals	**1.1**	**OP/kg removed**		48	(g)

2. Metal forming	**OP indicator**		**Total energy requirement**		**Comment**
			Typical [MJ/kg]	In the sources [MJ/kg]	
Extruding	**0.05**	**OP/kg removed**	2.2	2.2	(d)
Sheet metal forming	**0.2**	**OP/kg workpiece**	10	4.9…11.7	(g)
Cold forging	**0.75**	**OP/kg workpiece**	33.7	33.7	(g)

3. Casting & moulding	OP indicator		Total energy requirement		Comment
			Typical [MJ/kg]	In the sources [MJ/kg]	Estimates are indicated by an asterisk-sign: *
Metal casting	0.26	OP/kg	-	11.6	(g)
Pressure die casting	0.7	OP/kg	30*	15.4…48	(g)
Injection moulding	0.4	OP/kg	20*	4.3…69	(d, g, h)
Blow moulding	0.4	OP/kg	20*	8…23	(d, h)
Vacuum forming/ Thermoforming	0.1	OP/kg	6*	9…38	(d, g, h)
Deep drawing polymers	0.1	OP/kg	5	4.4…5.1	(e)
Polymer extrusion	0.2	OP/kg	7*	1.4…13	(a, d, h)
Film/sheet extrusion (unoriented), polymers	0.1	OP/kg	6	6	(d)
Film/sheet extrusion (oriented), polymers	0.5	OP/kg	24	23…25	(d) High value!
Calendering polymers	0.2	OP/kg	8	7.9	(d)
Rubber moulding	3.4	OP/kg	155	154.8	(g) Very high value!

4. Permanent joining	OP indicator		Total energy requirement		Comment
			Typical [MJ]	In the sources [MJ]	Estimates are indicated by an asterisk-sign: *
Welding (Spot/line)	**0.02**	**OP/m**	0.6/m	0.6…23/m	(g, h)
Wave soldering	**8.7**	**OP/m^2**	392 /m^2	392 /m^2	High value!, Used to fix components on Printed Circuit Boards (PCBs)

5. Surface treating	OP indicator	Total energy requirement		Comment
		Typical [MJ/m^2]	In the sources [MJ/m^2]	
Electro-plating	0.8 OP/m^2	37	2.8…45	(g, h) *e.g. with chrome*
Anodising	0.7 OP/m^2	32	32	*Used for aluminium*

6. Other manufacturing processes	OP indicator	Total energy requirement		Comment
		Typical [MJ/kg]	In the sources [MJ/kg]	Estimated values are indicated by an asterisk sign: *, extreme values and their sources by *italics*
Powder compaction	0.8 OP/m^2	37	2.8…45	Also called “sintering” very little waste, *little energy consumption because material is not re-melted several times*
Textile manufacturing, cotton	4.4 OP/kg	200*	*37.5*…244	[*DEPA 9*7, UMIPTEX 98], database Comprises wet-treatment (e.g. washing) and mechanical treatment (e.g. yarn spinning, knitting)
Textile manufacturing, polyester	2.8 OP/kg	134*	*37.5*…134	[*DEPA 9*7, UMIPTEX 98], database Comprises mechanical treatment (e.g. yarn spinning, knitting)

c) Transport Processes

Transport processes	OP indicator		Comment
Plane	0.26	OP/ton-km	11.7 MJ/ton-km (g) (large older jet)
Car	0.2	OP/km	Equals about 1 OP/ton-km (200 kg “pay load”)
Van	0.12	OP/ton-km	5.6 MJ/ton-km (g)
Truck	0.01	OP/ton-km	40 l crude oil (thus about 30 l fuel) per 100 km of a 40 t truck [Bey/Lenau 98a], p. 142
train	0.017	OP/ton-km	0.8 MJ/ton-km (g) (Diesel train)
ship	0.008	OP/ton-km	0.346 MJ/ton-km (g) (Container ship, i.e. most energy intensive type of ship transport)

d) Use & Consumption Processes and Consumables

Use processes	OP indicator	Comment
Electricity	0.25 OP/kWh	European average efficiency of electricity production: ca. 30 %, see table 3.3 in chapter 3 or [APME 98] Thermodynamically: 1 kWh = 3.6 MJ, Real, incl. efficiency: 1 kWh equals about 12 MJ
Natural Gas consumption	1.2 OP/kg	53.42 MJ/kg Gross calorific value [Boustead 99]
Natural Gas consumption	0.1 OP/m^3	Covers processing to “city gas” for stoves (amount: ca. 25 m^3/year in a household)
Water consumption	0.025 OP/m^3	From Danish waterworks, 1.14 MJ/m^3
Detergent (washing powder)	0.575 OP/kg	[UMIPTEX 98], database entry K50012
Detergent usage	0.012 OP/kg clothes	Derived from [UMIPTEX 98]

Compound use processes	OP indicator	Comment
Machine washing, 60º C	0.05 OP/kg	˜ 0.2 kWh per kg clothes [Zanussi 99], p. 44, [DEF 98], p. 17
Tumble drying, cotton	0.2 OP/kg	Spin-dried at 800 rpm, 70% rest humidity (before tumble drying) [Zanussi 99], p. 46, [DEF 98], p. 18
Tumble drying, synthetics	0.15 OP/kg	Spin-dried at 800 rpm, 70% rest humidity (before tumble drying) [Zanussi 99], p. 46
Coffee machine use	20 OP/year	5 times a week, 1 hour hot plate, coffee production, paper filters etc. included
A complete four-person household	400 OP/year	(gas stove, no washing/drying, central heating) about 1600 kWh per year, e.g. [Elsparefonden 99]
Drilling machine use	0.1 OP/year	Equals 0.5 kWh/per year (500 W, 1 h per year)
Water kettle use	24.4 OP/year	122 kWh/year (2000 W, 10 min /day)
Hair dryer use	6.2 OP/year	31 kWh/year (1000 W, 5 min /day)
Car use	3000 OP/year	15000 km /year
PC use	19 OP/year	95 kWh/year (260 W, 1 h/day), incl. CRT monitor

Fuels	OP indicator	Comment
Electricity	0.25 OP/kWh	European average efficiency of electricity production: ˜ 30 %, see table 6.4 respectively [APME 98] Thus: 1 kWh ˜ 12 MJ
Natural Gas consumption	1.2 OP/kg	53.42 MJ/kg Gross calorific value [Boustead 99]
Natural Gas consumption	0.1 OP/m^3	Covers processing to “city gas” for stoves (amount: ca. 25 m^3/year in a household)
Wood as fuel	0 OP/kg	CO_2-neutral
Gasoline	1.02 OP/kg	45.85 MJ/kg Gross calorific value [Boustead 99]

e) End-of-life Processes

End-of-life Processes	OP indicator	Comment
		See accounting rules in Chapter 6
Disassembly & re-use	0.5 OP/kg	Only little energy required (estimation)
Disassembly & Recycling/Re-melting	(0.5+X) OP/kg	X is the “fuel” value In a following cycle, the “fuel” part of the material has to be subtracted!
Shredding, separation & re-melting	(1+X) OP/kg	X is the “fuel” value In a following cycle, the “fuel” part of the material has to be subtracted!
Landfill	0 OP	Possible methane release
Incineration (thermal recovery)	Y OP/kg	Y is the feedstock value of the material, is only counted, if the material is NOT CO_2-neutral

Appendix II “One page” description of the OPM

This is a short ‘hands-on’ description of how to use the Oil Point Method (OPM) for environmental evaluations. You can use it to find energy-related environmental hot-spots in a product and two compare alternatives.

How to make an Oil Point evaluation

An Oil Point evaluation comprises three steps:

Step 1:	FOCUS	by setting a *GOAL*, by defining a *SCOPE* and by defining a *FUNCTIONAL UNIT*
Step 2:	EVALUATE	by making a *MODEL*, by finding *OIL POINT INDICATORS* and by calculating resulting *OIL POINTS*
Step 3:	INTERPRET	by checking *UNCERTAINTIES*, by regarding the *HOLISTIC CONTEXT* and by seeking *IMPROVEMENTS*

In **Step 1**, you FOCUS on what you want to examine by answering three questions:

GOAL *“Which decision do you want to support with the evaluation?”*
Is it a decision upon the material for a certain component or, maybe, upon alternative product solutions?

SCOPE *“Which product system do you consider?”*
Make up your mind, which processes in the life cycle stages ‘material production’, ‘manufacturing’, ‘transport’, ‘use’ and ‘end-of-life’ you want to look at?

FUNCTIONAL UNIT *“What is the Functional Unit you evaluate?”*
Define the service, which the product delivers for the customer. This so-called Functional Unit (FU) describes what exactly shall be compared. It should be defined as unambiguous as possible.

An example is given for a chair. It describes the product/service under four aspects:

- Quantitative aspects, e.g. the maximum weight, which the chair is supposed to support
- Qualitative aspects, e.g. whether the chair has armrests or not
- Temporal aspects, i.e. how long you expect the different stages and the whole life cycle to last
- Spatial aspects, i.e. in which countries you expect the life cycle stages to take place.

All compared alternatives have to fit to the same Functional Unit. Otherwise, not really equal products or services would be compared.

In **Step 2**, you EVALUATE your options by doing three things:

MODEL *Make a model of the product system you want to look at.*
This model should be a list of the life cycle processes to be considered in the life cycle stages, as you defined them in Step 1. Mark all items, which you are not sure of and which you, thus, have to assume.

OIL POINT INDICATORS *Find OP indicators for your the life cycle processes you need.*
Try to find them in the list given in the appendix. Otherwise estimate them by yourself and mark them as estimated.

OIL POINTS *Calculate Oil Points by multiplying Oil Point indicators and amounts occurring in the life cycle.*
You will get separated values for each life cycle stage and for the product as a whole.

In **Step 3**, you INTERPRET your results by, again, doing three things:

UNCERTAINTIES *Check influences of uncertainties in your evaluation*
There will be some things that you are quite sure of, e.g. the approximate total weight of the product, and some things, which you marked as assumption or estimation, e.g. the end-of-life scenario. You can check the importance of these uncertainties by varying them in extreme ranges and in this way find out, how much an influence on the overall result the single assumption has. For highly influential assumptions you may decide to look for better information.

HOLISTIC CONTEXT *See the result in a holistic perspective.*
Here, you basically check how important the decision at hand (as defined in Step 1) actually is. In doing so, you may find out that it, for instance, is not important which material a window frame has, if you are aware of the fact that the environmental impact related to heat loss through the window pane is more than hundred times that of the worst material.

IMPROVEMENTS *Seek improvement potentials.*
In this last element of Step 3, you analyse your result with questions in mind such as “Where in the life cycle would an improvement be most effective?”. Maybe not a different material but rather a different working principle would be best.

In order to remember all steps and elements of the OPM in mind, you may use the 3 x 3 matrix (see Chapter 6) and simply tick-off steps you finished.

Appendix III Products on the “List of undesirable substances”

The “List of undesirable substances”, compiled by the Danish Environmental Protection Agency [DEPA 98b], contains about 80 hazardous substances that are considered so dangerous that measures either have already been taken, for instance EU risk assessments, or that such measures are planned. The list is ordered after the names of the substances.

Including the list here is meant to give the user of the Oil Point Method an impression about hazardous substances that might be involved in a product or material option. The list is included because chemical aspects are not taken into account in the OPM.

Below, the DEPA list has been recompiled after product groups in order to facilitate a search, whether or not a certain product or ancillary material is likely to contain one or more of those undesirable substances. The three columns in the list contain the product, ancillary material or product group, the number of entries of this product or product group and, in some cases, the name of the undesirable substance(s) that lead to the entry.

Products/product groups	**Undesirable substance**	**Number of entries**
Accumulators	Nickel compounds	1
Adhesives	Phthalates	13
Ancillary substances in pesticides		2
Anti-fouling products	Copper compounds	3
Anti-rust products		5
Batteries	Mercury and mercury compounds	3
	Nickel compounds	
	Cadmium and cadmium compounds	
Binder products		1
Cadmium plating	Cadmium and cadmium compounds	1
Car waxes		1
Catalysers	Nickel compounds	1
Chromium plating	Chromium compounds	1
Cleaning products	Chromium compounds	3
	Tetrachloroethylene	
Coolant in foundries	Hexachloroethane	1
Coolant products		1
Coolants/lubricants		7
Corrosion inhibitors		2
Cosmetics	Methylglycol	13
	Dichloromethane	
Cosmetics Phthalates		1
Degreasing of metals	Hexachloroethane	1
Degreasing products	Trichloroethylene	3
cont.		

Products/product groups	**Undesirable substance**	**Number of entries**
cont.		
Dental fillings	Mercury and mercury compounds	1
Detergents and cleaning products	Linear alkylbenzene sulphonates (LAS)	1
Disinfectants		1
Dry cleaning	Tetrachloroethylene	1
Epoxy products		1
Filler products	Phthalates	1
Foam rubber	Hydrogenated fluorocarbons (HFC)	1
Fuel additives		1
Fungicides	Hexachlorobenzene	1
Hard white goods	Hydrogenated fluorocarbons (HFC)	1
Hardeners		1
Hydraulic fluids		1
Impregnated wood	Chromium compounds	5
	Copper compounds	
Insulating materials	Hydrogenated fluorocarbons (HFC)	1
Insulating windows	Sulphur hexafluoride	1
Insulators	Sulphur hexafluoride	1
Jewellery, buckles, spectacles, etc.	Nickel compounds	1
Jointing compounds		2
Lubricant oils/products		1
Lubricants		3
Odour additives		1
Paint and varnish strippers	Trichloroethylene	2
	Dichloromethane	
Paints	Chromium compounds	5
Paints and varnishes	Methylglycol	24
	Phthalates	
Pigments	Nickel compounds	2
	Cadmium and cadmium compounds	
Pigments and dyes	Copper compounds	1
Plastics	Brominated flame retarders	3
	Cadmium and cadmium compounds	
Preservatives		1
Printing inks	Phthalates	5
Protective gases	Sulphur hexafluoride	2
PVC		1
Refrigerating plants	Hydrogenated fluorocarbons (HFC)	1
Soft PVC	Phthalates	1
Soldering fluxes		1
Solvent products	Trichloroethylene	3
Solvents	Dichloromethane	4
Spray cans	Hydrogenated fluorocarbons (HFC)	1
Surfactants in detergents		1
Textile impregnation		1
Textiles	Brominated flame retarders	3
Toys (teething rings)	Phthalates	1
Tyres	Nickel compounds	1