A Review of the Theory and Practice of Life-cycle Assessment in the Car Manufacturing Industry

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LIST OF ABBREVIATIONS USED IN THE TEXT

CFCs	Chlorofluorocarbons
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CFRP	Carbon Fibre Reinforced Polymers
DfE	Design for Environment
EIA	Environmental Impact Assessment
EMAS	European Union Eco-Management and Audit Scheme
EMS	Environmental Management System
EPD	Environmental Product Declaration
IDIS	International Dismantling Information System
IMDS	International Material Data System
ISO	International Organisation for Standardisation
LCA	Life-cycle Assessment
LCI	Life-cycle Inventory Analysis
LCIA	Life-cycle Impact Assessment
MeRSy	Mercedes Recycling System
NEDC	New European Driving Cycle

NO_X	Nitrous oxides
OECD	Organisation for Economic Cooperation and Development
SETAC	Society for Environmental Toxicology and Chemistry
VOC	Volatile Organic Compounds
WSSD	World Summit on Sustainable Development

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BIOGRAPHICAL NOTES

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ABSTRACT

This paper reports on a literature-based survey of the theory and practise of life-cycle assessment (LCA) in the car manufacturing industry. Three levels of investigation were conducted, ranging from a broad industry scan, to a focus on four exemplary practitioners of LCA: DaimlerChrysler, Volkswagen, Volvo and BMW who becomes the subject of a detailed scan. Only 4 of the 21 companies surveyed in the broad scan are practising LCA. A greater proportion of car manufacturers must practise LCA if the industry hopes to achieve the UNEP challenge of enhancing car life-cycle eco-efficieny. It is found that there are limitations inherent in LCA: the methodology is complex, auditing is not mandatory, and LCA works best for simple components. It is therefore recommended that system boundaries be clearly defined and LCA studies be used to benchmark and improve on environmental performance *within* companies, as opposed to being used for inter-company comparisons.

KEYWORDS

Life-cycle assessment, life-cycle inventory analysis, cars, automotive industry, material and energy flow, BMW, DaimlerChrysler, Volkswagen, Volvo.

1 PROBLEM DEFINITION

The automotive industry produced 58 million vehicles in 2000 - on average, more than 150 000 vehicles a day. UNEP (2002) and the International Automobile Manufacturers association state that the future challenge is to further enhance the eco-efficiency of vehicles throughout the entire life cycle. This would require the implementation of life-cycle assessment (LCA) tools at all phases of a car's life.

This challenge is made all the more urgent by the fact that the total number of cars is expected to increase by 74 percent worldwide between 1997 and 2020 (UNEP, 2002). The total number of motor vehicle kilometres travelled is expected to increase by 86 percent worldwide in the same period (UNEP, 2002). Allied with this increase, is the fact that some 70 percent of the total energy required during the lifetime of a car is consumed during the use phase (Levin and Schweimer, 2002).

LCA, and its subcomponents, life-cycle inventory analysis (LCI) and life-cycle impact assessment (LCIA), help to classify, evaluate and mitigate the environmental impacts throughout all phases of a car's life cycle.

To what extent is the car manufacturing industry using LCA and its subcomponents (LCI and LCIA)? Which specific companies are leaders in this regard? What can be learnt from their experience? Is the tool being used meaningfully, resulting in actions that will mitigate the impact of the 1 billion vehicles to be produced between now and 2020 (assuming current production rates)?

This investigates these questions through a review of the practice of LCA and its related tools in the car manufacturing process. The manufacturing process is a broad term referring to the phases of: design, raw materials gathering, assembly, distribution, use and recycling (or disposal) of cars.

This paper provides an overview of global car manufacturers who are using LCA. Thereafter discussion focuses on how, why and where these tools are being used in BMW, DaimlerChrysler, Volvo and Volkswagen.

With the problem defined and the context established, the next section describes the approach adopted in this research.

2 DESCRIPTION OF APPROACH

An information strategy was adopted to navigate the course of this investigation into the theory and practice of LCA in the car manufacturing industry, and to choose which manufacturers deserved greater focus.

The strategies of a predominantly rational approach that requires comprehensive information or a satisficing approach to information collection were rejected in favour of the synthesis offered by Etzioni (1968): mixed scanning.

He defines this approach as *"the combination of wide but not deep examination of facts and options with more detailed study of select sub-sectors, chosen in the first or second round of scanning"* (Etzioni 1991: p. 46). The term scanning refers to the collection, analysis, and evaluation of information.

Mixed scanning begins with a broad investigation, often without in-depth information or analysis. On the basis of this investigation an appropriate sub-strategy is then chosen, before examining in detail some options within the sub-strategy. Subsequent investigations, based on more detailed information and analysis, follow a particular line of thought until it is realised that one of the previous assumptions or decisions must be modified and the process is repeated. The final investigation thus takes form gradually in an incremental and iterative way (Hill, 2003).

Mixed scanning is a hierarchical form of information collection that incorporates higher-order, fundamental investigations with lower-order incrementalism (Etzioni, 1967; 1991). It provides advice on how to go about the process of data collection (Hill, 2003).

Cognisant of the time and resource limitations on the one hand, and the desire for investigative comprehensiveness on the other, three levels of scanning were chosen for this review (table 1).

Level of scanning:	**Breadth of review:**	**Subject of review:**	**Sources:**
Major strategy	Broad	Theory of LCA, overview of the car manufacturing industry.	Broad literature review of published material and UNEP automotive industry sector report prepared for the World Summit on Sustainable Development (WSSD).
Appropriate sub-strategy	Medium	Focus on 4 best performing car manufacturers for a detailed review. These case studies are chosen on the basis of the results of the broad scan.	Publications and annual environmental reports (present editions only) from four car manufacturers: BMW, DaimlerChrysler, Volkswagen and Volvo.
Examination in detail of an option within the sub-strategy	Narrow	Focus on one company for a detailed assessment of their use of LCA tools in the manufacturing process. The results from this scan are compared with the ideal theory review.	BMW's annual environmental report (containing data for the years 1996 to 2000 inclusive) and BMW website information.

Table 1: Three levels of scanning were chosen as a strategy to navigate the course of this investigation into the use of LCA, and to choose which manufacturers deserved greater focus (source: author).

3 BROAD SCAN OF THEORY AND PRACTICE OF LCA

This section is the first and broadest of three levels of scanning. It contains a review of the theory behind LCA in general (section 3.1), and then a review of the practice of LCA in the car manufacturing industry specifically (section 3.2).

3.1 *Broad scan 1: review of the theory of LCA*

3.1.1 *The relationship between LCA and sustainable development*

Sustainable development has been defined as development which aims at "meeting the needs of the present without compromising the needs of future generations" (WCED, 1987).

It must first be understand how LCA fits into a conceptual framework that contributes to the goal of sustainable development.

Referring to Figure 1, below, there is a distinction between life cycle thinking as a *concept*, and LCA as a specific *methid.* Complementary to life cycle thinking, other concepts related to sustainable development include:

- cleaner production,
- design for environment (DfE), and
- industrial ecology (Udo de Haes, 1996).

On a more practical level a further distinction can be made between analytical methods and policy instruments. Complementary to LCA, other examples of analytical methods are:

- Substance Flow Analysis (SFA),
- Risk Assessment, and
- Ecological Modelling.

Policy instruments aimed at sustainable development include Ecolabelling, Integrated Chain Management and, Environmental Impact Assessment. These policy instruments may well use the analytical methods for their underpinning (Udo de Haes, 1996). An example concerns the role of LCA (and more specifically LCI) in environmental auditing.

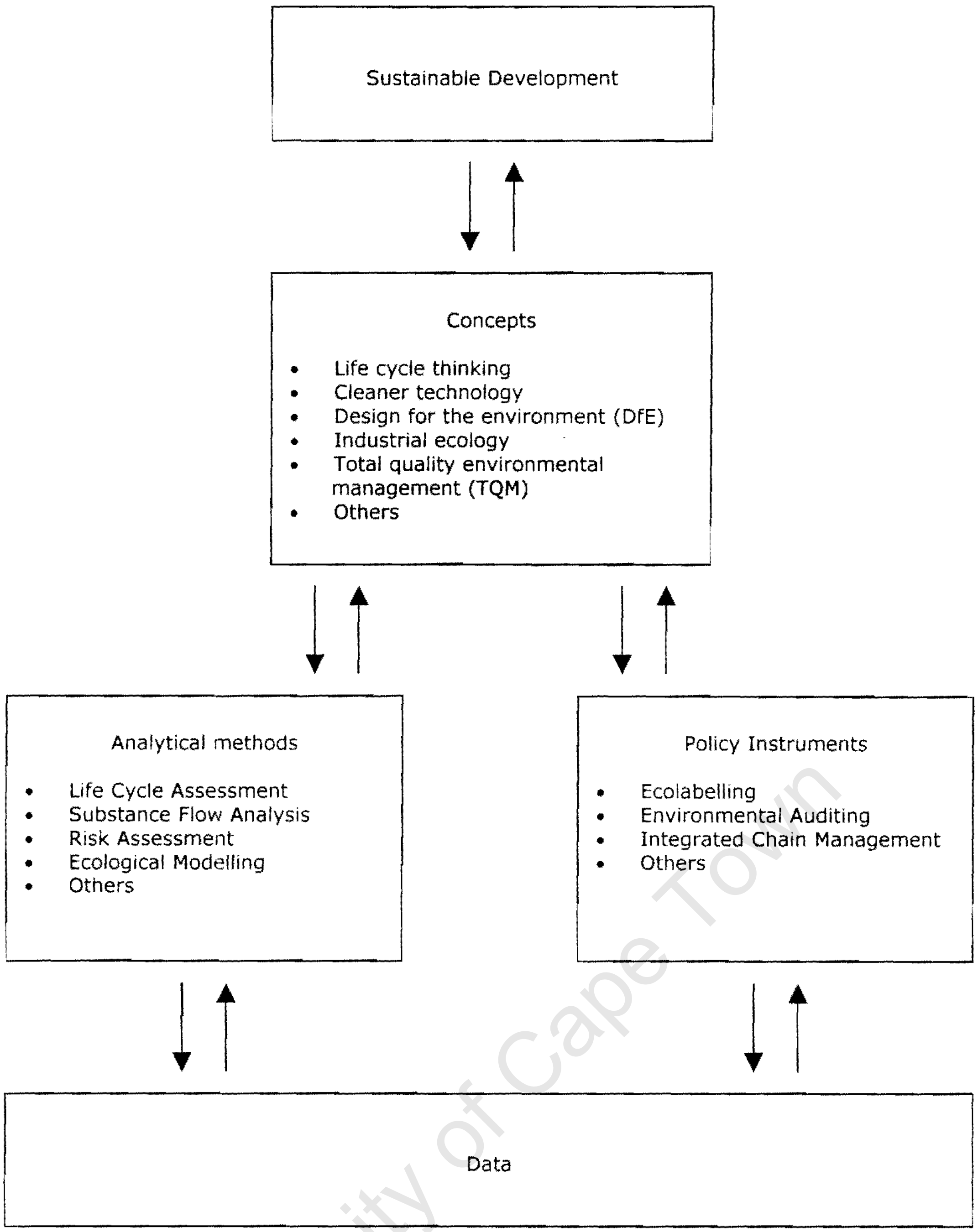

Figure 1: The relationship between LCA and the goal of moving society to a style of development (and consumption) that is sustainable. Note the distinction between life cycle thinking as a *concept*, and LCA as a specific *method*. (source: Udo de Haes, 1996).

In Figure 1, the distinction between life style thinking as a *concept*, and LCA as a specific *method* is clearly highlighted. This is necessary to understand when investigating the car manufacturing industry, since manufacturers make use of both levels: for instance, DaimlerChrysler focus conceptually on life style thinking as part of their Design for Environment (DfE) programme (DaimlerChrysler, 2002),whereas BMW focus on the analytical method of LCI as part of their environmental performance programme.

Having established the context of LCA as both a way of thinking and as an analytical method within the overarching goal of sustainable development, an investigation into the theoretical basis for the practice of LCA follows.

3.1.2 *The theory underpinning LCA practice*

The theory behind the practice of LCA in the car manufacturing industry does not significantly differ from the practice of LCA in any other industry, except in differences of scale and complexity. It will therefore suffice to review and comment on the standard framework for LCA as put forward by the Society for Environmental Toxicology and Chemistry (SETAC). This framework has been incorporated into the ISO 14 000 series (and more specifically into the ISO 14 040 standard), which is *"already in place with most international [vehicle] manufacturers"* (UNEP, 2002: p. 27).

3.1.3 *The theoretical framework for LCA*

The practice of life-cycle assessment is a comprehensive and complex effort, and there are many variations. Nonetheless, there is general agreement on the formal structure of LCA, which contains three stages and is illustrated in Figure 2 (SETAC, 1993):

1. goal and scope definition,
2. inventory analysis, and

3. impact analysis, each stage being followed by interpretation of results.

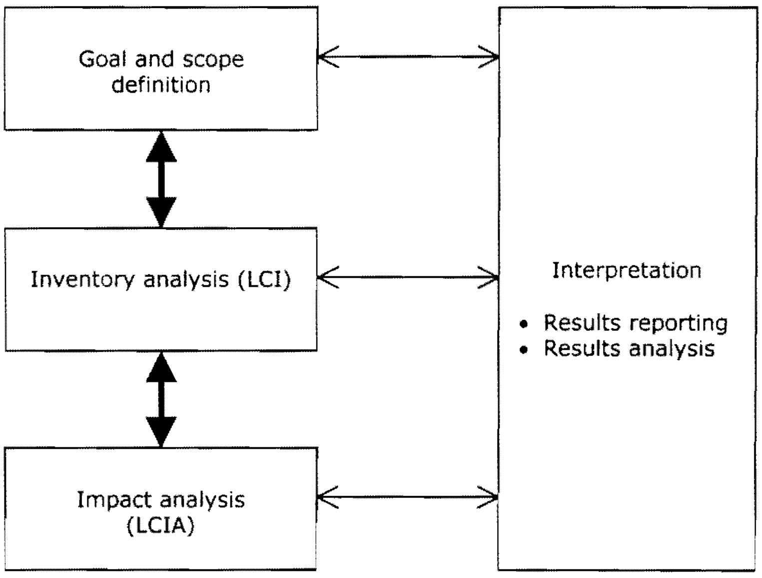

Figure 2: Stages in the life-cycle assessment of a manufacturing activity (source: SETAC, 1993 and Von Blottnitz, 2003)..

In Figure 2 the wide arrows represent the basic flow of information. Interpretation of results occurs at each stage, allowing the possibility of revising the environmental attributes of the activity under focus

3.1.3.1 Goal setting and scope definition

Before an LCA is begun, the purpose for the activity must be defined. Typically LCA studies are performed in response to specific questions. The nature of the question determines the goal and scope of the study (Boguski, 1996).

The most common LCA goal is to conduct an assessment of the environmental attributes of a specific product or process and to derive information from that assessment on how to improve environmental performance.

If this exercise is conducted early in the design phase, the goal may be to compare two or three alternative designs. If the design is finalised, the product is in manufacture, or the process is in operation, the goal can probably be no more than to achieve minor changes in environmental attributes at minimal cost and minimal disruption to the existing operation (Graedel, 1998).

Quantification of the goal requires quantification of each assessment step. Therefore quantitative goals should be adopted only when one is certain that adequate data and assessment tools are available.

Graedel (1998: p. 29) recommends that the scope of the assessment is best established by asking a number of questions: *"Why is the study being conducted? How will the results be used? What level of detail is needed?"* Furthermore, it must be recognised that life-cycle assessment is an iterative process, and that the scope may need to be revisited as the LCA proceeds.

3.1.3.2 Study boundaries: Don't shift the problem

The choice of LCA boundaries has a significant influence on the time, scale, cost, and tractability of an LCA. The choice of boundaries also affects the result of an LCA. Von Blottnitz (2003) recommends that the system boundary is drawn 'from cradle to grave', so that the inputs are primary resources and the physical outputs are the set of all flows to the environment. This integrative approach avoids the bias in a study as a result of shifting environmental problems outside the system boundary. Three common types of problem shifting can be identified (Von Blottnitz, 2003):

1. Shifting the problem from one stage of the life cycle to another; for example, substituting a hazardous raw material with a less hazardous type, which may require more intensive (and waste producing) pre-processing.
2. Shifting from one problem to another; for example, replacing a gaseous emission problem with gas scrubbers that produce solid waste or liquid effluent.
3. Shifting the problem from one location to another; for example, switching from coal-firing to electric power moves the emissions from the plant to the power station site.

To avoid the shifting of problems, consistent attention must be given to identifying and documenting what life cycle phases lie inside and outside the system boundaries.

The four car manufacturers reviewed in this study did not perform satisfactorily in this step of the LCA process. With the exception of BMW, their documentation did not clearly indicate the system boundaries of their LCA studies.

3.1.3.3 Life-cycle Inventory Analysis (LCI)

In this stage, material and energy balances form the foundation for identifying and quantifying all material and energy flows that cross the system boundary (as illustrated in Figure 3). This stage results in an inventory table and inventory flow diagram, which quantifies the inputs and outputs per functional unit produced (for example, energy consumed for each car produced).

The four car manufacturers reviewed in this study all performed satisfactory LCI studies. Allenby and Graedel (1995: p. 109) confirm this by noting that, in general *"inventory analysis is by far the best developed [component]"* of LCA.

The major variation between the four chosen car LCA studies was the choice of system boundaries. These were chosen as either:

1. the entire company, including all productions plants and installations worldwide (in the case of BMW), or
2. a single plant (in the case of Volvo), or
3. individual cars (in the case of Volkswagen), or
4. individual components or raw materials (in the case of DaimlerChrysler).

Each of these four scales of LCI studies applies a different focus to the manufacturing process, and answers different questions about material and energy performance.

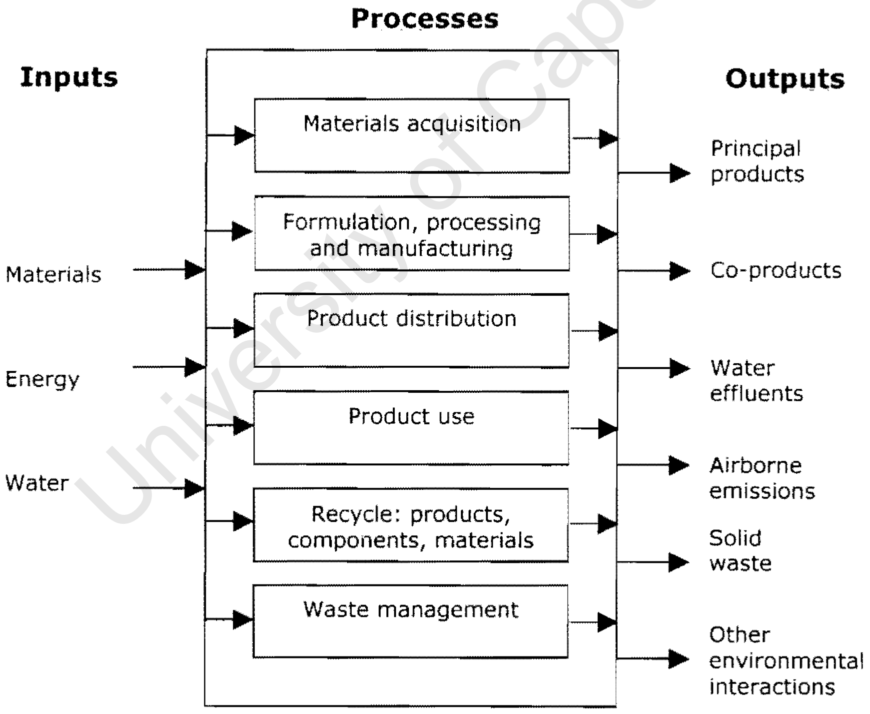

Figure 3: Elements of a life-cycle inventory analysis (LCI) (source: SETAC, 1991).

Referring to Figure 3, most of the LCIs reviewed in this study failed to include the last two processes of the life cycle: recycling and waste management. Volkswagen omitted these processes because they could not account for or predict how vehicles are recycled or disposed. They alluded to changing legislation (especially in Europe) as a cause for uncertainty in this regard (Volkswagen, 2001).

3.1.3.4 Life-cycle Impact Assessment (LCIA)

In the first step of LCIA, stressors are identified in the inventory analysis as those items that have the potential to produce changes in the environment (Allenby and Graedel, 1995). Stressors are developed outside of industry, by the environmental science community. The stressors will be identified as part of a standard engineering analysis on some aspect of production.

The second step in LCIA implies the prioritising of the impacts that have been determined (Allenby and Graedel, 1995). In effect, this step constitutes the application of risk analysis to the full spectrum of environmental concerns. In the case of the car manufacturing industry, the collaboration required for this between industrial ecologists and environmental scientists must take place across national boundaries, because multinational corporations cannot rationally design products for countries that have widely differing priority rankings for environmental concerns.

A major complicating factor is that risk prioritisation is not only scientific but also reflects the value system of the community performing the prioritisation. It thus requires harmonisation across cultures as well as agreement on scientific issues.

By combining LCA inventory results with stressors, a car manufacturing process might be found, for example, to have a substantial impact on local water quality, a modest impact on regional smog, and a minimal impact on stratospheric ozone depletion (Dutilh *et al.*, 1996). Depending on the value-laden priorities given to these impacts, differing engineering solutions will be sought.

3.2 *Broad scan 2: LCA in the car manufacturing industry*

3.2.1 *Performance since the Rio Earth Summit*

Since the Rio Earth Summit in 1992, the automotive industry has made considerable progress in its efforts to promote sustainable development (UNEP, 2002). During the manufacturing phases, advanced technological solutions have been implemented to minimise energy and water consumption, as well as emissions and waste output. This is evidenced by the use of LCI across various companies and many manufacturing plants (BMW, 2002; Volkswagen, 2001).

During the use phase, which accounts for some 70 percent of the total energy required during a car's lifetime (Levin and Schweimer, 2002), major achievements include reduced fuel consumption and widespread use of catalytic converters leading to a reduction of exhaust emissions. For example, under optimal conditions, 100 of today's new cars produce the same amount of emissions as a car built in the 1970s (UNEP, 2002). This is a direct result of new engine technologies and advanced exhaust gas treatment systems. All companies publish regular reports to keep the public informed about progress in this highly relevant area (UNEP, 2002).

3.2.2 *The implementation of LCA in car manufacturing companies*

Only 4 out of the 21 car manufacturers represented in the UNEP (2002) automotive sector report to the WSSD are reporting the practice of LCA (and its subcomponents, LCI and LCIA) in their operations.

Table 2 highlights where LCA and related tools are being used in industry:

Company	**Project or programme**	**Activity**
BMW	LCA	All major plants are subject to an intensive materials and energy flow analysis (LCI), as part of LCA studies aimed at mitigating environmental impacts (BMW Group, 2002).
DaimlerChrysler	Design for Environment (DfE)	LCAs are implemented as a Design for Environment (DfE) commitment. This means that the ecological impacts of raw materials are evaluated from cradle-to-grave (UNEP, 2002).
Volkswagen	LCI	Detailed and complete balance sheets of all the materials and the energy used for specific car models are being compiled. This allows a comparision of diesel and petrol engines in a single model across the entire life cycle (Levin and Sweimer, 2002; Volkswagen, 2001).
Volvo	Environmental Product Declaration (EPD)	EPDs, which describe the environmental effects of a product throughout its life cycle, have been published (Volvo, 2000). These are based on extensive life-cycle assessments covering the production, use and end-of-life phases (UNEP, 2002).

Table 2: The practice of LCA in car manufacturing companies (source: author).

3.2.3 LCA used in designing recycling initiatives

Worldwide, measures are being implemented to develop a vehicle-recycling infrastructure. LCA techniques are contributing to these efforts (UNEP, 2002). Close co-operation with external suppliers facilitates the application of LCA methods which focus on all phases: material acquisition, vehicle production, delivery, use, service and recycling. LCI studies enable manufacturers to obtain detailed information on material flow and energy consumption. This information allows more informed recycling decisions, and materials choices based on an understanding of the entire life cycle. German and Swedish carmakers have already implemented this approach (UNEP, 2002).

3.2.4 The use of LCI in environmental management

Management systems including EMAS (European Union Eco-Management and Audit Scheme) and the worldwide ISO 14 000 series are already in place with most international car manufacturers (UNEP, 2002). They aim to minimise negative environmental impacts with regard to water and energy use, emissions and waste associated with the production process. Continuous performance improvement requires the quantification of matter and energy flows using LCI studies. This has resulted in significant improvements in resource efficiency in the automotive sector on a global scale (UNEP, 2002).

4 MEDIUM SCAN: FOCUS ON FOUR MANUFACTURERS

In the medium scan of this section, focus will be given to these four companies who can be regarded as industry leaders in the use of LCA in the car manufacturing process:

- BMW: *"The BMW Group has quality management and environmental management systems in place at all of its production plants - including locations in developing countries"* (UNEP, 2002: p. 29). A review of BMW's exhibition at the WSSD also demonstrated their use of LCA in product development (Maharaj, 2002).

- DaimlerChysler: *"At DaimlerChrysler, LCAs are implemented as a Design for Environment (DfE) commitment"*(UNEP, 2002: p. 29).

- Volkswagen: *"Life-cycle inventories have been implemented by the Volkswagen Group"* (UNEP, 2002: p. 29).

- Volvo: *"The Volvo Group have published environmental product declarations with detailed product information based on extensive life-cycle assessments"* (UNEP, 2002: p. 29).

These four best performing car manufacturers were chosen as a result of the broad scan (section 3) and will now be discussed, in turn, in sections 4.1 to 4.4. The source material for the medium scan is publications and annual environmental reports (present editions only) published by the four manufacturers.

4.1 Focus on BMW

4.1.1 *Good environmental management across the entire company*

The BMW Group has quality management and environmental management systems in place at all of its production plants - including locations in developing countries (UNEP, 2002). As a result, the company has been able to improve their material and energy throughput performance in the period 1996 to 2000:

- CO_2 emissions per vehicle produced were reduced by 15 percent,
- process water requirements per vehicle produced were reduced by 35 percent,
- wastewater disposal per vehicle produced was reduced by 16 percent, and
- energy consumption per vehicle produced was reduced by 20 percent (BMW Group, 2002).

In the same period, overall solvent use fell by 30 percent. This is primarily the result of increased use of water-soluble paints. BMW will further reduce the use of solvents with its advanced powder coating technology, a solvent-free final coat devoid of harmful emissions (BMW Group, 2002).

4.1.2 *Questionable LCA practice on a per-component basis*

BMW practises comparative life cycle assessment for components within the product development phase (BMW Group, 2002). It is not explicitly stated how many of the total components are subject to this approach. Instead BMW engineers state their progress in terms of the total weight of the car. For instance, the current BMW 3-series model contains 90 kilograms (6 percent of total weight) of recycleable plastics. Total weight has been reduced by 7 kilograms (0.4 percent of total weight) following the integration of aluminium and magnesium into the car's chassis (BMW Group, 2002). These appear to be small weight and recycling improvements for a single car, but may have a large cumulative effect over many road-kilometres travelled and cars recycled. These long-term effects are not documented.

BMW Group (2002: p. 28) states: *"In compliance with ISO 14 040 eco-balance (LCA) guidelines, a detailed analysis is made of the potential environmental impact of each product"* (own underline). It would appear from this statement that the use of the LCA on a per-product basis is widely applied. However, this statement is doubtful since the results of these analyses remain unpublished either in the annual environmental report or on the Internet.

4.1.3 Adherence to LCA methodology

BMW has clearly documented their LCA methodology for performing LCAs, as is illustrated in Figure 4. BMW was the only LCA practitioner reviewed to explicitly publish their LCA methodology.

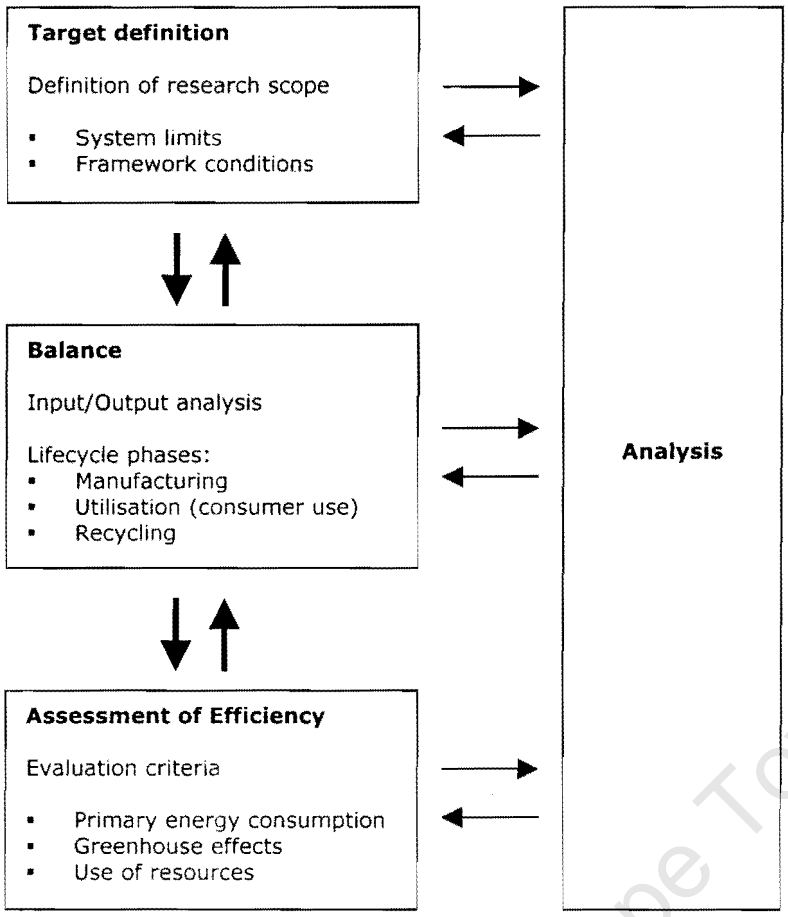

Figure 4: Stages in the BMW methodology of the life-cycle assessment of a component. (source: BMW Group, 2002).

At each stage in Figure 4, the results are interpreted, thus providing the possibility of revising the environmental attributes of the activity being assessed. Their framework corresponds very closely with the theoretical ideal put forward by SETAC (1993) (Figure 2).

The boundaries of the LCA studies for components include design and engineering operations, as well as manufacturing and assembly, sales and service, and final recycling of end-of-life vehicles (BMW Group, 2002). It excludes raw materials acquisition and transport between phases.

4.1.4 Focus on the use phase of the life cycle

During the entire lifecycle of a car, the environmental impact is highest during the consumer use phase (BMW Group, 2002; Levin and Schweimer, 2002). Because BMW product planning and development is aimed at reducing environmental impact for the total lifecycle of the product, much attention is paid to the use phase.

4.1.5 Focus of the recycling phase of the life cycle: Design for recycling

Engineering new vehicle components involves an assessment of the LCI study of those components to evaluate their suitability for recycling. The BMW Recycling and Disassembly Center (RDZ) in Lohhof, Germany conducts detailed disassembly analyses (BMW Group, 2002). These studies take a close look at the amount of time and the tools required for disassembling end-of-life vehicles. This information is then used to determine whether the construction techniques and materials used in the vehicle are suitable for recycling (BMW Group, 2002). The results of these recycling studies remain unpublished either in the annual environmental report or on the Internet.

4.1.6 Critical evaluation

BMW is making widespread use of LCI techniques on a per-plant basis to improve material and energy flow performance in its facilities. These improvements are well documented. Their documentation of LCA methodology and clarification of system boundaries is exemplary.

BMW's use of LCA methods on a per-component basis is unsatisfactorily documented, and therefore the claimed widespread application of such methods is questionable.

4.2 *Focus on DaimlerChysler*

4.2.1 *Overview*

At DaimlerChrysler, LCAs are implemented as a Design for Environment (DfE) commitment. This means that the ecological benefits - including recyclability - of a raw material are evaluated from cradle-to-grave. For instance, although using lighter aluminium components in building a car leads to less fuel consumption, more energy is needed on the raw material side. On the other hand, recycling aluminium requires relatively less energy than other materials. DfE research also extends to the use of recycled and renewable materials (DaimlerChrysler, 2002; UNEP, 2002).

4.2.2 *Emissions*

Through a combination of improved design and efficient emission control systems, DaimlerChrysler was able to reduce the various types of emissions across its vehicle range by 70% to 95% from 1985 to 2000 (UNEP, 2002).

Building on this, the company has set an environmental target of reducing CO_2 emissions over the entire product life cycle (DaimlerChrysler, 2002). To achieve this, comparative LCA studies will provide an appraisal of the CO_2 emissions embodied in individual components and overall vehicle concepts.

4.2.3 *Recycling*

Product development begins with the selection of suitable raw materials and ends with recycling-friendly production processes. These make it possible to re-use or recycle used components at a later stage.

DaimlerChrysler (2002) claims to uses high quality secondary raw materials in place of expensive primary resources. In the plastics sector, preference is given to recyclable materials or recycled raw materials. The extent to which this is being practised in the E-Class range is illustrated in Table 3.

	Use of renewable raw materials (e.g. flax, hemp, sisal and others)		Use of recycled plastic raw materials	
	Weight	Components	Weight	Components
Current E-Class	31.4 kg (2 % of total weight)	50	23 kg (8.5 % of total plastic, 1.5% of total weight)	38
Former E-Class	20.5 kg (1 % of total weight)	21	21 kg (12.1 % of total plastic, 1 % of total weight)	n/a

Table 3: The use of renewable materials and recycled plastic materials in the current and former E-Class models (source: DaimlerChrysler, 2002).

It can be seen from Table 3 that the use of renewable and recycleable materials currently offers minor weight savings. The primary energy savings achieved by these materials over the lifetime of the car is undocumented.

4.2.4 *Take-back and disassembly*

Efficient disassembly and recycling concepts mean that fewer parts from end-of-life passenger cars and commercial vehicles have to be landfilled. The Mercedes

Recycling System (MeRSy) has been introduced in Germany, Austria, Switzerland and the Benelux states (DaimlerChrysler, 2002).

In Germany, under the terms of a voluntary undertaking by the car industry, DaimlerChrysler has taken back end-of-life vehicles that are a maximum of 12 years old, free of charge (DaimlerChrysler, 2002). The EU End-of-Life Vehicle Directive, which came into force in Germany in mid 2002, obligates every car manufacturer to take back end-of-life vehicles that meet certain requirements, free of charge.

4.2.5 *Case study: comparative LCA of past and present models of the Mercedes-Benz E-Class*

DfE technicians have drawn up a comprehensive LCA study comparing the current and former model of the Mercedes-Benz E-Class.

The production phase of the new E-Class consumes approximately 20 gigajoules more than its predecessor, owing to the increased use of lightweight materials. This is an 11 percent energy increase for the production phase (see Figure 5). However, given the new model's lower fuel consumption during the use phase, it takes approximately 65,000 kilometres to amortize the difference in energy input. Over a 250 000 km life, the new model consumes about 100 gigajoules less energy, equivalent to a 10 percent energy reduction for the entire life cycle (DaimlerChrysler, 2002).

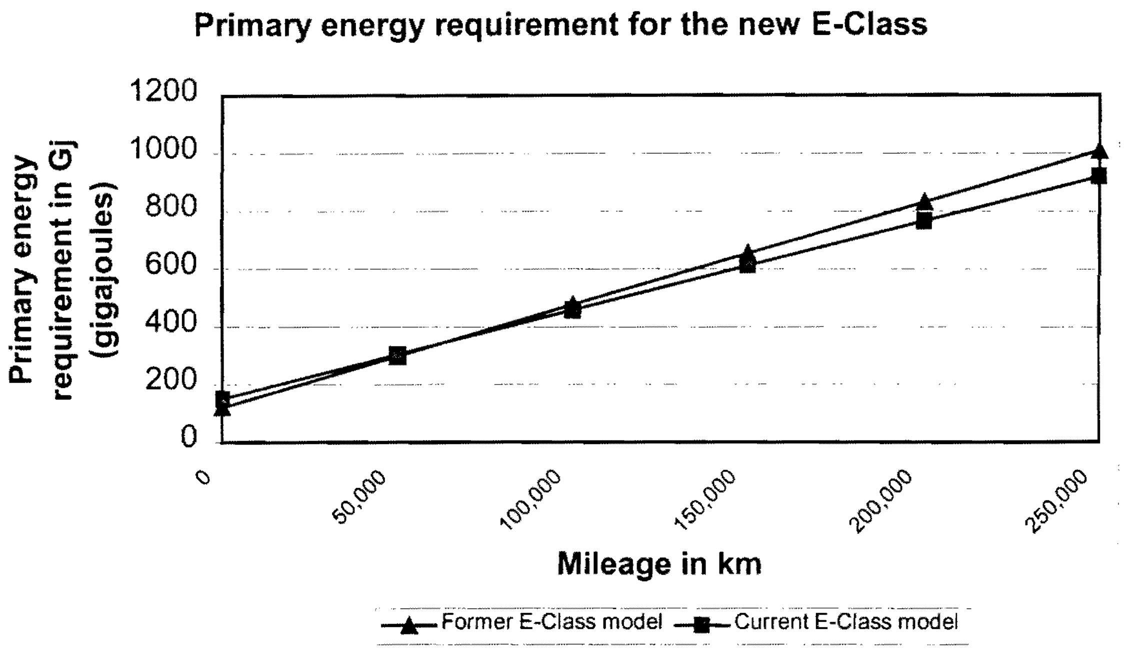

Figure 5: Primary energy requirements for the current and former E-Class. At 65,000 km into the use phase, the current E-Class amortizes the energy invested in lightweight materials during the production phase (source: DaimlerChrysler, 2002).

Figure 5 shows the 10 percent energy saving achieved over a 250 000 km vehicle lifetime. Though this saving is only a fraction of the total primary energy requirement, if the next three models achieve the same percentage energy reduction, then the primary energy requirement will be at 65 percent of the original.

Lightweight materials are not always the more energy efficient option. An example is illustrated in Figure 6.

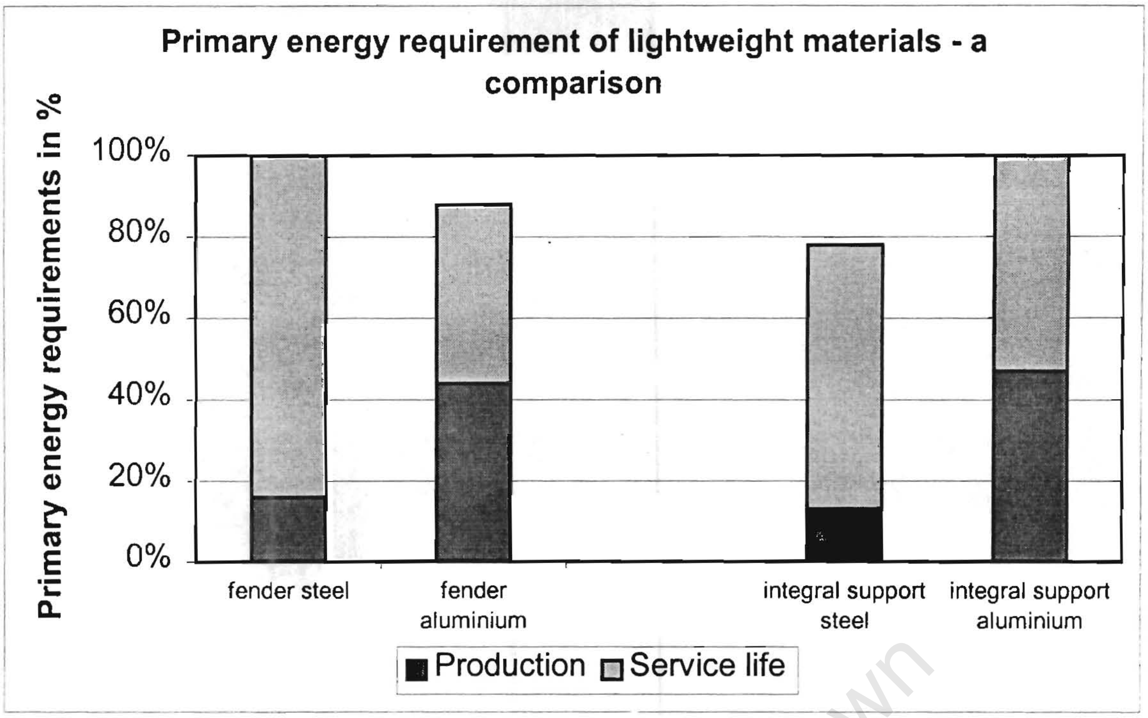

Figure 6: A comparison of the primary energy requirements of aluminium and steel components. 'Service life' refers to the energy required in the use phase, most of which is ascribed to petrol (source: DaimlerChrysler, 2002).

Figure 6 shows that in the comparison of steel and aluminium for the production of different components, the LCI comes out in favour of aluminium for fenders and steel for integral supports (which link the engine and body shell) (DaimlerChrysler, 2002). This illustrates why DaimlerChrysler looks at specific components when considering the use of lightweight materials, and not at subassemblies or the vehicle as a whole.

4.3 *Focus on Volkswagen*

4.3.1 *LCI studies for different models*

Since 1996, Volkswagen has performed LCI studies on four of its models: the Golf A3, the Golf A4 (petrol engine, 55kW), the Golf A4 TDI (diesel engine, 66 kW) and the Lupo 3L TDI. Comparative analysis of these documents allows environmental compatibility strengths and weaknesses to be identified in each model.

Between the first and fourth inventories, the cost and effort of performing an LCI study for an entire vehicle was reduced by more than 50 percent (Volkswagen, 2001). Nonetheless, owing to the prohibitive time and effort required, Volkswagen does not perform LCI studies on all its models.

To account for the use phase of a car (driving, refuelling, servicing), Volkswagen (2001) assumes a driving pattern based on the statutory New European Driving Cycle (NEDC) for measuring consumption and emissions.

4.3.2 *Analysis and conclusions drawn from LCI studies*

A conclusion drawn from these studies is that the initial production phase of raw materials (steel, light metals and plastics) is of greater environmental relevance (in terms of primary energy, CO_2, SO_2, NO_X and particulate emissions) than the actual process of transforming them into a car (Volkswagen, 2001).

Analysis clearly shows that the majority of emissions in the use phase are attributable to CO_2 (which doesn't contribute to local pollution), with hydrocarbons, sulphur dioxides and particulates only accounting for a tiny proportion (all of which contribute to local pollution).

4.3.3 *Significant emissions reductions can be achieved by lower r.p.m.*

LCI reveals that the consumer generates the majority of a vehicle's environmental impact during its use phase. 73 percent and 68 percent of the primary energy required by the Golf A4 and Lupo 3L TDI respectively is consumed while the vehicles are on the road. As much as 30 percent of this energy could be saved by driving in a more careful and environmentally responsible way (Volkswagen, 1999).

Changing the way one drives can also reduce exhaust emissions by between 25 percent and 50 percent.

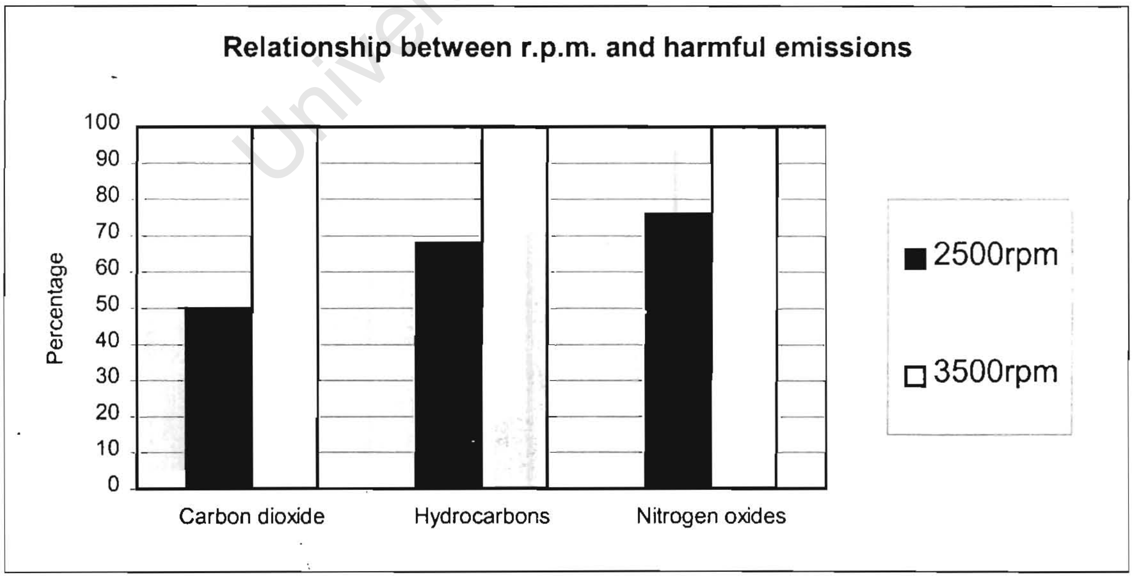

Figure 7: Relationship between r.p.m. and harmful emissions. Figures are percentages. (source: Volkswagen, 1999).

4.3.4 *Case study: LCI study of the Golf A4 (petrol and diesel models)*

For this study by Levin and Schweimer (2002) the system boundary included only those production processes directly involving raw materials, the car as a product, its operation and its end of life. Production of the required plants and infrastructure were not considered. A summary of the findings follows.

4.3.4.1 Energy use

The primary finding of this LCI is that the majority of energy is consumed during the use phase. Approximately 8 percent of total energy is needed to manufacture the vehicle, 12 percent to mine the materials and a further 8 percent to provide the required fuel. The remaining 73 percent is attributable to the use phase, of which the majority is attributable to the calorific value of the fuel burned during the 150 000km of driving and to the spare parts (tyres) (Levin and Schweimer, 2002). It was a new discovery for the authors to find that more energy is required to mine the materials than to produce the vehicle.

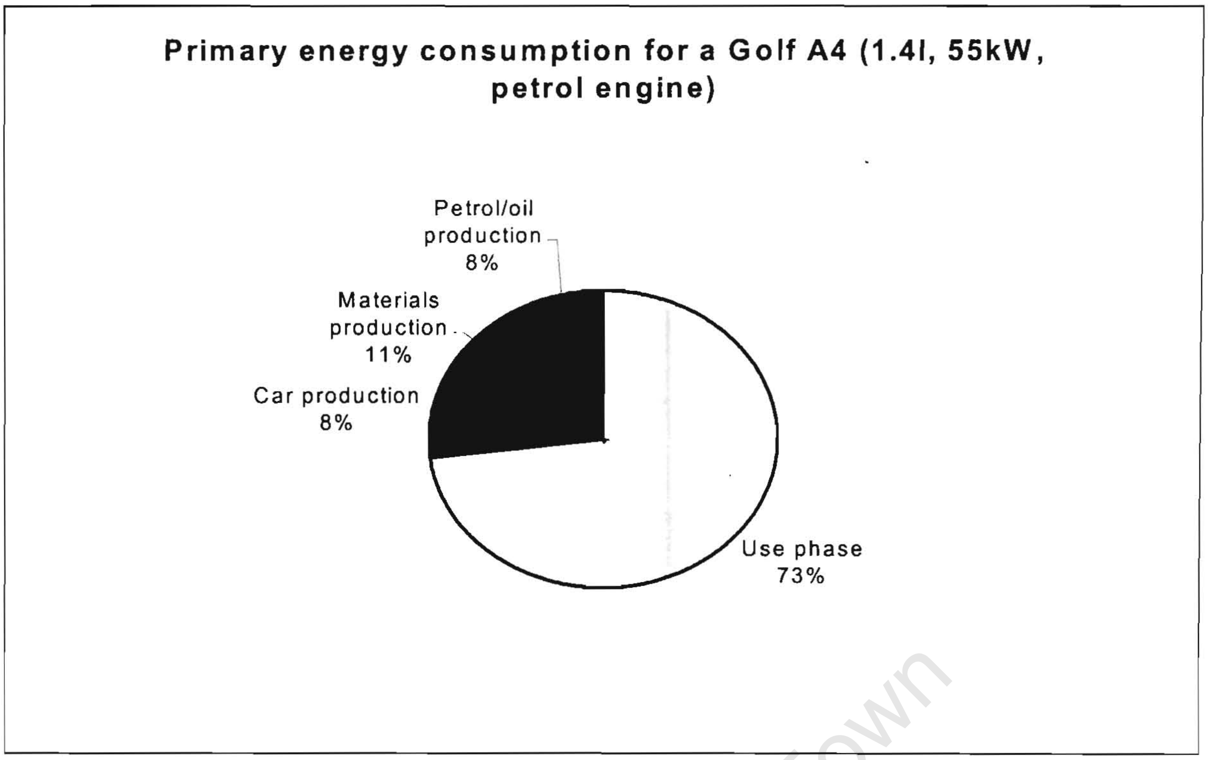

Figure 8: The total primary energy consumption for a Golf A4 (1.4l, 55kW, petrol engine) over 150 000km over 10 years. Note how the materials production (pre-production) phase requires more energy than the production phase itself (source: Levin and Schweimer, 2002).

4.3.4.2 Emissions

The majority of metal and chlorine emissions to the atmosphere and water occur during the mining of the raw materials. The majority of hydrocarbon and sulphuric oxide emissions are generated during the production of the fuel. Interestingly, the major contributors to pollution are outside the car manufacturer's factory.

The dominant factor during the use phase is energy demand (fuel consumption) and accordingly, CO_2 emissions, which make up around 77% of total emissions (Levin and Schweimer, 2002).

4.3.4.3 Water consumption

The 95 cubic metres of water consumed over the lifetime of an average car can be broken down as follows (Levin and Schweimer, 2002):

- electric power generation (used in manufacture): 46 m^3
- fuel production: 23 m^3
- material production: 10 m^3
- other factors: 9 m^3
- car washing: 8 m^3
- Total: 95 m^3

It is interesting to note that an average vehicle requires 90 times its own body weight in water over its lifetime (including manufacture and use).

4.3.4.4 Recycling

The car is the consumer article with the highest rate of recycling – even higher than for paper (Levin and Schweimer, 2002). The reason for this is that a car cannot simply be thrown into a rubbish container. Also, metal recycling techniques have reached very high standards. Used synthetics are increasingly being subjected to thermal recycling (Levin and Schweimer, 2002).

4.3.4.5 Comparison of the Golf A4 (petrol engine, 55kW), the Golf A4 TDI (diesel engine, 66 kW) in terms of emissions

A comparison here shows that, over its entire life cycle (150 000km over 10 ten years), the TDI Golf (diesel) emits three tonnes less CO_2 than its petrol engine counterpart.

In addition, on the fuel front, the production and distribution of petrol for the Golf A4 generates 40 kilograms more hydrocarbons than in the case of diesel. However, these advantages of the diesel engine are offset by higher NO_X and particulate emissions.

4.3.4.6 Other results

According to the authors (Levin and Schweimer, 2002) this LCI study brings to light some specific aspects relating to the passenger car, including that:

- a large number of materials are specially developed for the car industry,
- a large number of individual components make up a passenger car,
- energy is consumed primarily in the use phase and in the pre-production phases and,
- relative to the production phase only a few types of pollutant emissions (CO_2, NO_X) are predominant in the use phase.

4.3.5 The International Material Data System (IMDS) for cars

Instead of performing LCI studies on all its models, Volkswagen focuses on adding environmental data to the International Material Data System (IMDS) for cars (Volkswagen, 2001). This is an internet-based database set up by the German Association of the Automotive Industry (VDA). It supplies automakers and their partners with information about the materials make-up of individual car components. This information is required to comply with threshold limits (e.g. 2 grams of chromium per vehicle) set up by the European Union's (EU) End of Life Vehicle directive.

At the other end of the life cycle, Volkswagen offers dismantling data to recycling operators across Europe. The International Dismantling Information System (IDIS) provides dismantling data for all vehicles produced since model year 1985 on a CD-ROM (Volkswagen, 2001).

4.3.6 External Auditing

The Volkswagen environmental Report 2001/2002 has been audited by KPMG Germany. This is noteworthy considering that none of the other companies surveyed in the medium scan (BMW, DaimlerChrysler and Volvo) included such notice of an external audit.

4.4 *Focus on Volvo*

4.4.1 *LCAs incorporated into Environmental Product Declarations (EPDs)*

One of Volvo's goals in its 2000 environmental report is: *"Every new product must have a lower environmental impact than the one it replaces"* (Volvo, 2000: p. 9). Comparable data are required to enable the environmental impact of different products to be compared. Thus, an environmental product declaration (EPD), which describes the environmental effects of the product throughout its life cycle, is both an essential tool and the first step towards achieving the overall goal.

Volvo has already published EPDs with detailed product information based on extensive life-cycle assessments. Data from production, the use phase and end-of-life treatment are published (UNEP, 2002).

4.4.2 *Suppliers and contractors involved in environmental activities*

Since suppliers outside Volvo's own organisation influence the life-cycle environmental impact of a Volvo product significantly, the company is involved in extensive environmental cooperation with its suppliers and contractors. Among other aspects, the global environmental requirements imposed by Volvo on its suppliers extend to the implementation of environmental management systems (EMS), the reporting of environmental data and the restricted use of certain chemical substances (Volvo, 2000).

To restrict the use of chemicals in the life cycle, Volvo maintains a 'black list' of prohibited chemicals, a 'grey list' of products whose use must be limited and a 'white list' of substitutes for hazardous chemicals (Volvo, 2001b; Volvo, 2001c; Volvo, 1998). To facilitate the choice of chemicals, Volvo maintains a web-based database (MOTIV) containing detailed information on over 6,000 chemical products.

4.4.3 *Inventory flows published for all Volvo plants*

The Volvo Group has been publishing detailed environmental data since 1995. Data reporting is based on an internal standard that focuses on a number of key areas, such as: use of chemicals, energy and water consumption, emissions to air and water, waste and noise (Volvo, 2001a).

At the end of the year 2001, the Volvo Group had majority ownership of 52 production plants around the world. Data is recorded for each of them as part of their EMS activities. Data for each facility is supplied in the following categories (Volvo, 2001a):

- Consumption
  - Energy (MWh)
  - Water (m^3)
- Emissions
  - CO_2 (tones)
  - Solvents (tones)
  - NO_X (tonnes)
  - SO_2 (tonnes)
- Waste ouput
  - Hazardous waste (tonnes)

The environmental impact of operations and the environmental programmes conducted at each plant depend on the nature of the operation concerned, the size of the plant, local conditions and the length of time the plant in question has belonged to the Volvo Group (Volvo, 2001a).

Volvo purports to record data for 'operation activities' (Volvo, 2001a). It is not clear what life cycle phases are being referred to by the phrase 'operation activities'. This is because the system boundaries for operation studies are not explicitly stated.

4.5 *Observations from medium scan*

BMW presented the most comprehensive reports for overall flows of energy and materials within the company as a whole.

DaimlerChrysler and Volvo present LCI studies for individual car models and company plants as a whole. However, their methodology is not as explicitly stated, nor their system boundaries as clearly indicated as BMW's.

Though Volkswagen have documented the most comprehensive LCI studies on individual car models, they will be discontinuing this practice due to prohibitive time and financial cost. They have not reported on overall company energy and material flows.

5 NARROW SCAN: BMW

The narrow scan is a focused examination of an option within the medium scan. Weighing up the observations from the medium scan (section 4.5), BMW is chosen as the best option for a narrow scan focussing on their use of LCA tools (including LCI and LCIA) in the car manufacturing process. The results from this narrow scan are compared with the ideal theory review performed in the broad scan (section 3.1).

5.1 Recycling practices

5.1.1 Plastics recycling

Metals make up 75 percent of a car's total mass and can be easily recycled (BMW Group, 2002). Metal recycling technology is well developed and therefore BMW instead focuses on plastics recycling. BMW specialists concentrate on the increasing proportion of plastics used in modern cars to reduce weight and increase fuel efficiency (BMW Group, 2002). The current BMW 3-series cars, for example, contain around 162 kilograms of plastic materials. This is 15 percent more than the previous model. Nearly 90 kilograms of these plastics can be economically recycled in compliance with BMW recycling standards (BMW Group, 2002).

The proportion of plastics in an average BMW vehicle is currently around 12 percent. Depending on the model, 14 to 15 percent of these plastics are themselves made from recyclates. The goal is to gradually increase this proportion depending on market conditions and technical feasibility (BMW Group, 2002).

5.1.2 *End-of-life recycling*

In Germany a network was created with nearly 100 BMW-approved recycling firms and 200 vehicle drop-off points. The company guarantees environment-friendly end-of-life vehicle recycling in all major EU countries (BMW Group, 2002).

5.2 ***Reducing weight to minimise emissions during consumer use phase***

During the entire lifecycle of a car, the environmental impact is highest during the consumer use phase. Volkswagen studies show that approximately 70 of primary energy for the entire life cycle is consumed during the use phase (Levin and Schweimer, 2002). Fuel economy is thus an important criterion in the Impact Assessment stage of an LCA. BMW is conducting research into lightweight car construction. The BMW Z22 is an output of such research – it is 35 percent lighter than a model with comparable performance, interior space and comfort (the BMW 530i touring) (BMW Group, 2002).

The vehicle weighs 1 100 kg (10kg/kW) and uses mechatronic (mechanical systems with electronic control) systems to replace current purely mechanical systems. For instance, steer-by-wire and brake-by-wire in the Z22 replace the mechanical steering and hydraulic brake systems (BMW Group, 2002). The Z22 is in the research and development phase; it is unclear when it will ready for series production.

5.2.1 *LCA studies of light weight carbon fibre reinforced polymers (CFRP)*

The Z22 uses carbon fibre reinforced polymers (CFRP) which shows great weight saving potential in car body construction. CFRP is 50 percent lighter than steel and up to 30 percent lighter than aluminium. Along with lower weight, the material is reported to perform well in crash testing and is corrosive resistant (BMW Group, 2002).

The prospects of using carbon fibre reinforced polymers still has one major drawback: CFRP structural parts from end-of-life vehicles are not suitable for a mechanical recycling due to the high disassembly costs. Consequently, they will be thermally recovered in the future as a component of the automotive shredder residue (BMW Group, 2002).

BMW specialists conduct environmental LCA studies on CFRP materials and components. This process involves evaluating the overall impact of the material considering both vehicle recycling and lightweight construction. A minor impact on environment in the production phase may be regarded as acceptable, if compensated by emissions reductions in the use phase.

In a comparison with a BMW 5-series side frame made of steel, the lighter CFRP frame performed satisfactorily in terms of environmental compatibility, i.e. energy consumption, potential greenhouse effects, and resource depletion (BMW Group, 2002).

5.3 *Company wide LCI studies*

Key environmental factors in car production include energy and water consumption, wastewater disposal, exhaust gas and noise emissions, waste and hazardous materials, carbon dioxide, and the use of solvents.

As a result of their environmental management system (EMS) combined with inventory analysis, BMW has been able to improve their material and energy throughput performance in the period 1996 to 2000 (BMW Group, 2002).

BMW Group has summarised their energy and water input as well as their wastewater, CO_2 and solid waste output. The inventory flow diagrams below indicate the improved performance. Figure 9 shows the inventory flows for a single average car produced in 1996. This can be compared with Figure 10, which shows the inventory flow a car produced in 2000.

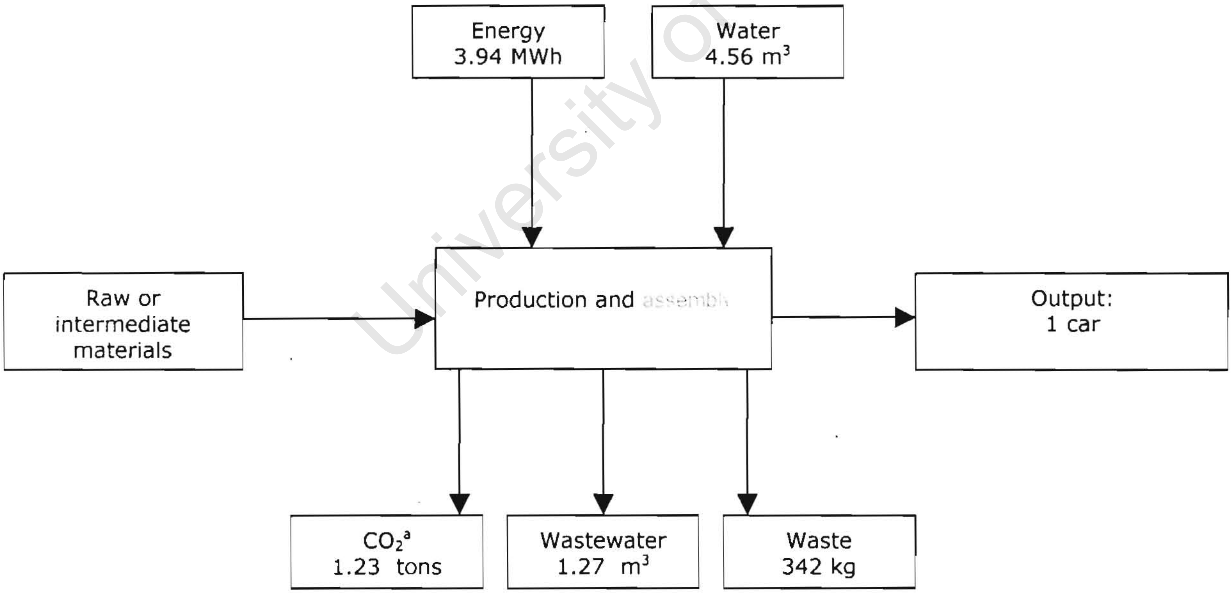

Figure 9: Inventory flow diagram for the average, individual BMW car produced and assembled in the year 1996 (source: author; data: BMW Group, 2002).

[a] Includes CO_2 emissions of external electricity production.

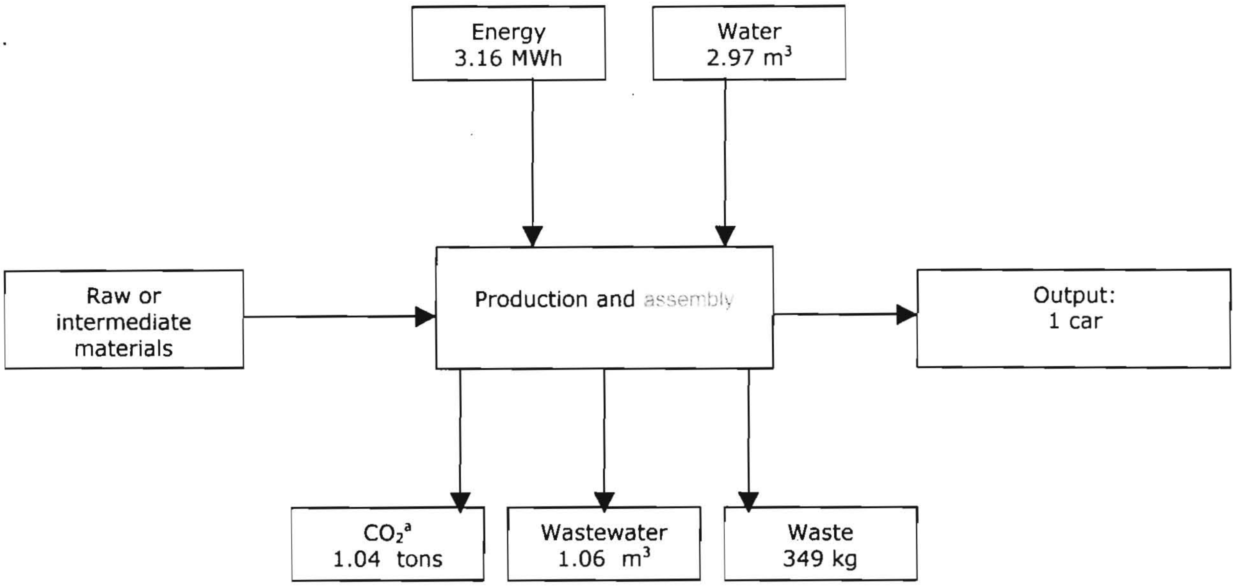

Figure 10: Inventory flow diagram for the average, individual BMW car produced and assembled in the year 2000 (source: author; data: BMW Group, 2002).

[a] Includes CO_2 emissions of external electricity production.

It can be seen from Figures 9 and 10 that between 1996 and 2000, the energy and material flow required for the production of a single BMW car improved in all areas except solid waste. Water requirements were reduced by 34 percent, energy requirements were reduced by 19 percent, and CO_2 emissions were reduced by 15 percent.

Figure 11 is a detailed inventory flow diagram for a single car produced in 2000. Figure 12 shows the inventory flows associated with all car production in BMW in the year 2000. Though BMW's energy and material flows across the entire company were better in previous years (i.e. 1996 – 1999), this is simply because fewer cars were being produced (BMW Group, 2002). Comparing the inventory flow for a single car versus the entire company leads to different conslusions: eco-efficiency is improving on a per car basis, but the company is nevertheless consuming more resources because they are producing a greater number of cars.

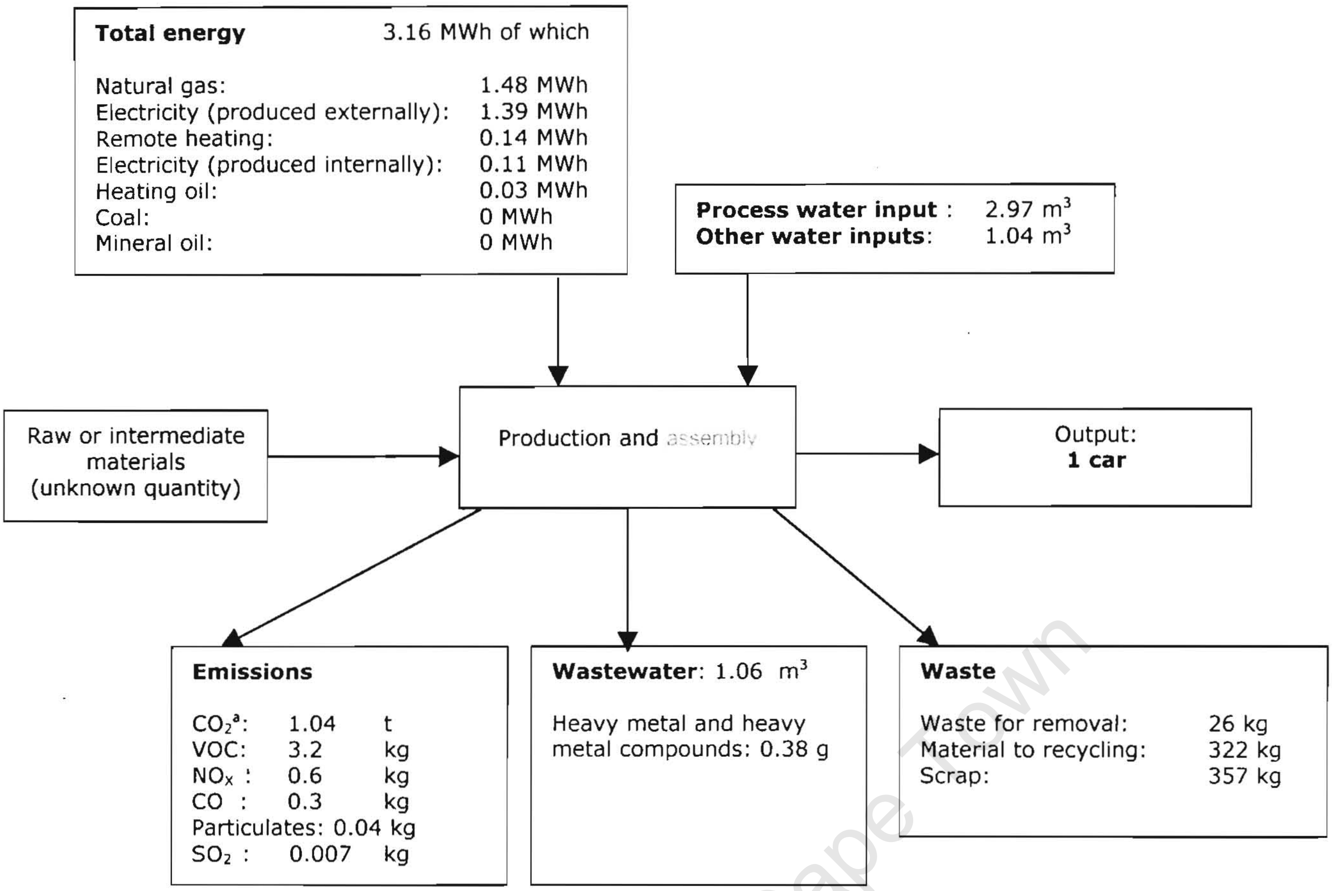

Figure 11: Detailed inventory flow diagram for the average, individual BMW car produced and assembled in the year 2000. (source: author; data: BMW Group, 2002)

[a] Includes CO_2 emissions of external electricity production.

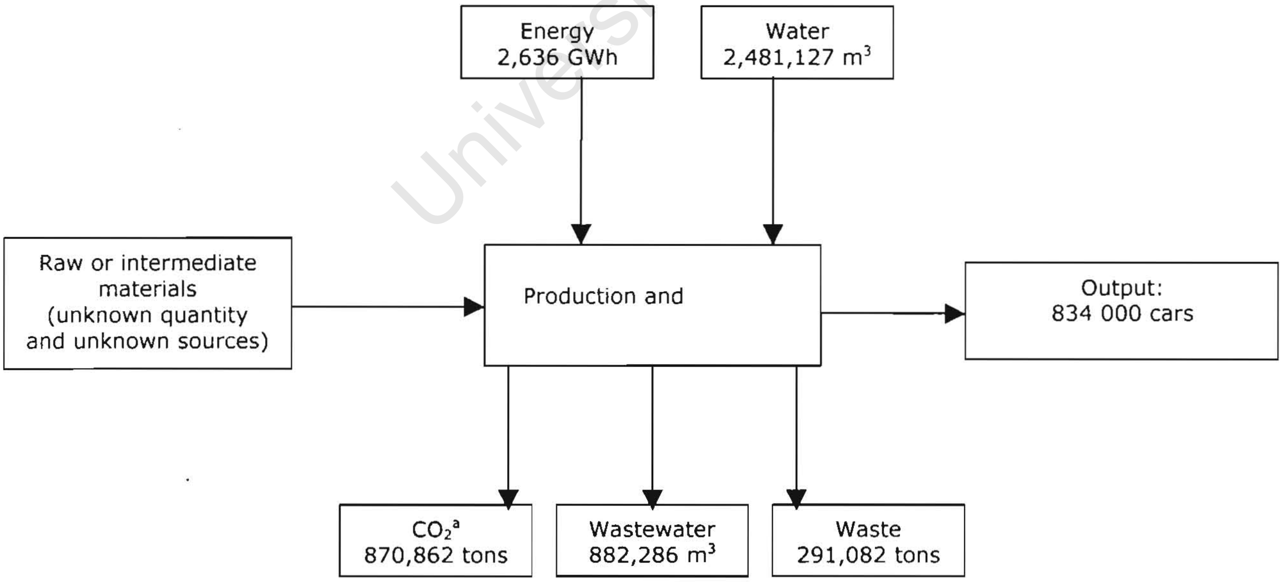

Figure 12: Inventory flow diagram for all BMW car production and assembly sites for the year 2000 (source: author; data: BMW Group, 2002).

[a] Includes CO_2 emissions of external electricity production.

5.3.1 Unspecified LCI system boundaries and other issues

The product life cycle involves a number of stages between acquiring raw materials, product use and final disposal. These stages are illustrated in Figure 13. LCI studies, such as those conducted by BMW, must be careful to clarify and document the stages in the process for which data was collected. Because the system boundary was not explicitly stated for these LCI studies, it is most likely that this data refers only to the product manufacture phase in the BMW plant. It therefore excludes raw materials acquisition, product use and recycling (or disposal).

Another issue is that there is no documentation indicating that these LCI studies were externally audited.

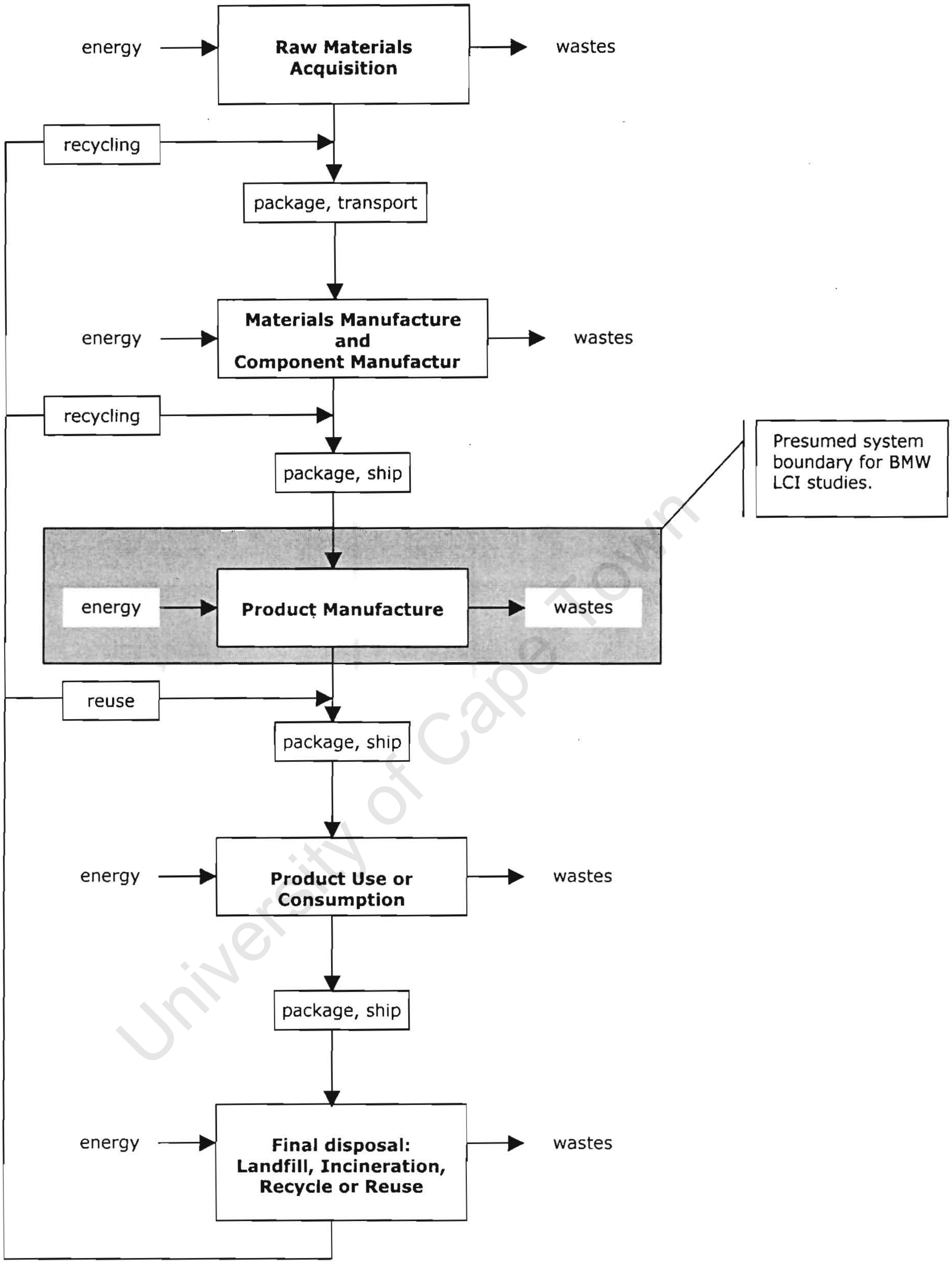

Figure 13: General materials flow diagram for a product life cycle. The presumed system boundary for the BMW LCI studies is shown (source: author, after Boguski, 1996 and Graedel, 1998).

5.4 *Supply chain integrity*

Car manufacturers procure many components from other companies who specialise in component manufacture. The car manufacturer then simply assembles all the gathered components. This procurement process is illustrated in Figure 14.

Thus a related problem of unspecified system boundaries *within* a car manufacturer, is the issue of unspecified boundaries *between* the car manufacturer and suppliers of components and parts.

This would mean that BMW's inventory analysis excludes the energy, material and waste flows of components manufactured elsewhere. These flows are hidden because they are higher up the supply chain, outside the study boundary.

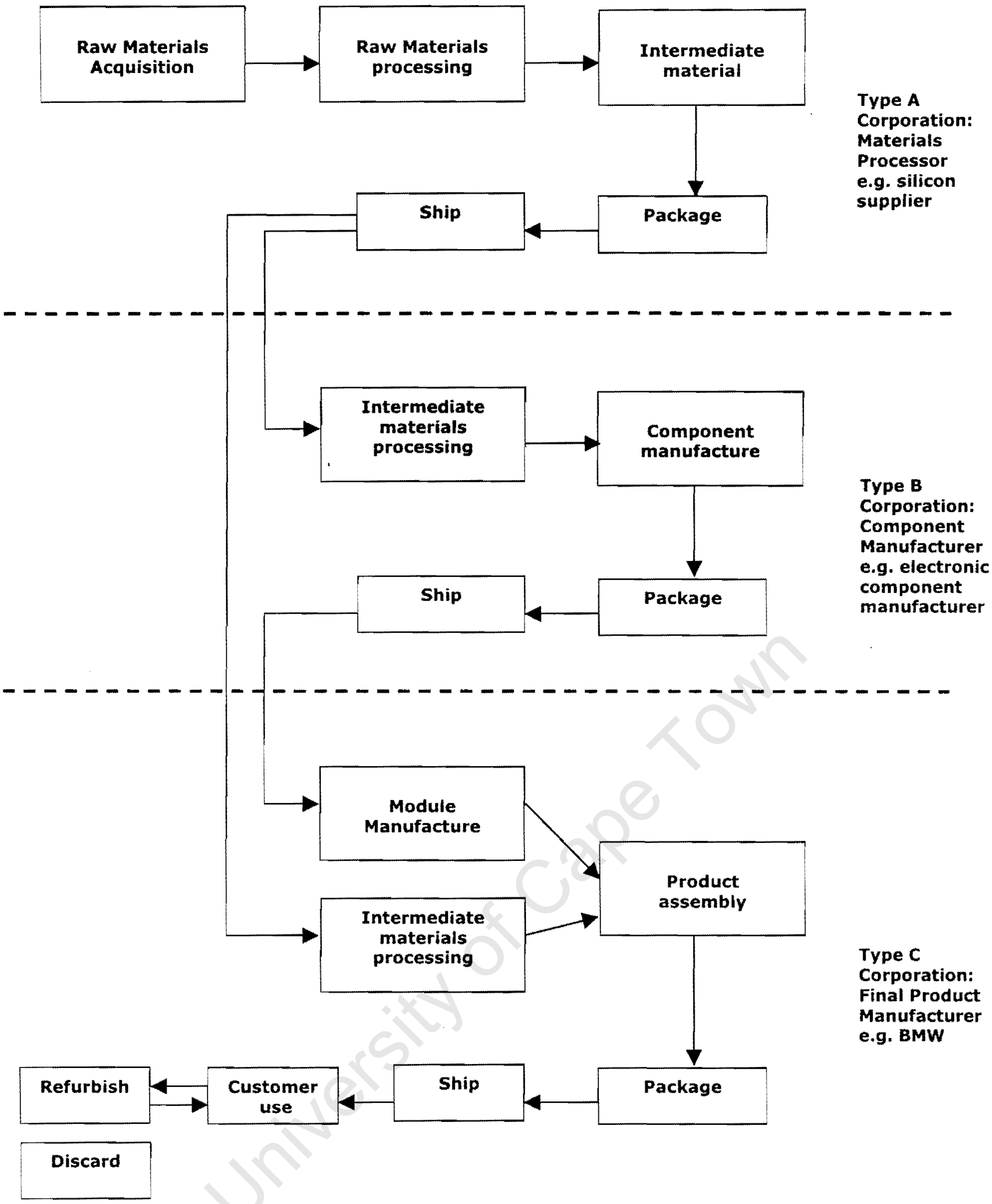

Figure 14: The interrelationships of product life stages for corporations of Type A (materials processors), Type B (component manufacturers), and Type C (final product manufacturers). The examples given are for the case where electronic components are supplied to BMW by another company, that company itself having procured raw material (e.g. silicon) from another company higher up the supply chain (source: Graedel, 1998).

5.5 Critical evaluation

BMW's LCA efforts are at the level of company-wide LCI studies. These LCI studies provide data for monitoring performance as part of their EMS programmes on production plants. The data set is restricted to those indicators that can be measured with relative ease at a production plant: energy (natural gas, electricity, heating oil and others), water, emissions (CO_2, VOC, NO_X, CO, particulates, SO_2), wastewater and solid waste.

LCI data for individual cars is extrapolated by divided total energy and material flows by the number of cars produced. This method provides meaningful environmental performance information, but without a prohibitive investment of time or finances.

A shortcoming of this approach is a lack of focus on improving the environmental performance of individual car models or components. BMW needs to implement and report the use LCA on individual models, sub-assemblies and components.

6 OBSERVATIONS FROM THE BROAD, MEDIUM AND NARROW SCANSS

6.1 LCA is not practised widely in the car manufacturing industry

Only 4 out of 21 car manufacturers surveyed by UNEP and the International Automobile Manufacturers association were documented as practising LCA (UNEP, 2002).

6.2 LCA methodology is too complex

A fundamental concern about present LCA methodologies is that they are too complex and detailed to be useful in the real world (Allenby and Graedel, 1995). An effective LCA methodology must be able to quickly and easily identify, then differentiate between, critical environmental impacts (Allenby and Graedel, 1995).

Of the four companies surveyed in the medium scan, only BMW made publicly available their documentation of their LCA methodology (BMW Group, 2002). Their LCA framework corresponds very closely with the theoretical ideal for an LCA framework as proposed by SETAC (1993).

Of the four companies surveyed in the medium scan, all are performing LCI studies that conform satisfactorily to the ideals dictated by LCA theory.

Although not required by ideal theory (SETAC, 1993), a shortcoming in their practise of LCA is that only one of the four companies surveyed in the medium scan had their report externally audited.

6.3 LCA was designed for simple products

A second limitation of most existing LCA methodologies arises because they were developed for fairly simple products: disposable diapers, drinking cups and so on (Allenby and Graedel, 1995). As of 1995, no satisfactory LCA studies had been done on a more complex item such as a car (Allenby and Graedel, 1995).

It is possible to adapt an LCA process to accommodate its inherent limitations. For example, when considering the use of lightweight materials, DaimlerChrysler perform LCA studies on single components rather than on whole subassemblies or the vehicle as a whole (DaimlerChrysler, 2002). In this way, the LCA for an entire vehicle is broken down into simpler, more manageable parts.

6.4 Data limitation considerations and system boundaries

While the concept of life-cycle assessment is one that is readily understood and appreciated, its implementation often proves intractable - or at least impractical - because of problems relating to

- data needs,
- time,
- financial expense and
- uncertainty regarding defendability of results (Graedel, 1998).

If the boundaries for an LCI are tightly constrained, the data may be readily available and easy to acquire. Broad boundaries, in contrast, create substantial data requirements (Graedel 1998). Conscientious LCA assessors evaluating the same product can easily produce differing results as a consequence of the way in which the system boundary was set up and information was collected.

The effect of this is that it is difficult (if not impossible) to compare LCA studies between one car manufacturer and another. For instance, it would meaningless to compare an LCI study of a Volkswagen Golf A4 and its equivalent in the BMW range. It would be only be a useful comparison if the system boundaries and the data collection methods were identical in both studies.

6.5 *Impact assessments are value-laden*

LCA studies are finding that much of the 'low-hanging fruit' has been picked (i.e., actions with high benefit/cost ratios), and that efforts to find and harvest more 'fruit' raise ethical and value-laden questions (Graedel, 1998). For example, is it preferable in a car manufacturing operation to use a volatile organic solvent or to utilise more energy to do the same job with an aqueous solvent (Graedel, 1998)?

Implicit within the use of LCA tools, is the need for a set of values by which to weigh up the results of an LCA study and make appropriate decisions. These values are not universally agreed, but will need to be established for each new study to suit the culture, organisation and bio-physical peculiarities of the study area.

6.6 *Not all impacts can be assessed*

To capture the total environmental impacts of any product, process or organisation is virtually impossible. The operative principle is to attempt to capture as many of the *interactions* with the natural environment as is possible (Bebbington and Gray, 2001). The simple reasons for this are that

1. impacts are many and various, and
2. create domino effects that lead to consequences far removed in space and time from the factory outlet pipe or smokestack.

These two very simple principles touch upon the essential nature of systems thinking and ecology (Goldsmith *et al.*, 1972).

7 CONCLUSION AND RECOMMENDATIONS

The car is regarded as an environmentally significant product (BMW Group, 2002). Its use has a fundamental impact on people and the environment. Worldwide, the proportion of CO_2 emissions from cars is around 5.5 percent of the total from anthropogenic sources (OECD, 2001).

In light of these facts and the previous section, the following recommendations are made:

- LCA needs to be practised by more companies in the car manufacturing industry. This is necessary if the industry hopes to meet the UNEP (2002) challenge of enhancing the eco-efficiency of vehicles throughout the entire life cycle.
- LCA (as well as LCI and LCIA) studies should be made available to the public. It is possible that more than 4 out of 21 companies surveyed are performing LCAs (UNEP, 2002), but there is no documentation by individual companies to indicate this.
- LCA studies should be used to benchmark and improve on environmental performance *within* companies. These studies can be used to:
    - Compare year-to-year inventory performance across the entire company.
    - Compare inventory performance across manufacturing or assembly plants within a company.
    - Compare the environmental impact of different vehicle models.
- LCA studies should not be used to compare the performance of different car manufacturers. This is due to the lack of a standard industry practice regarding data gathering and setting of study boundaries.

- More attention needs to be paid to the establishment and documentation of system boundaries in LCA studies.
- The automotive industry needs to discuss whether the projected growth rate of car use is really sustainable with regard to the gas emissions, urban congestion, and road construction. The UNEP (2002) report fails to address these fairly obvious concerns(Wennberg, 2002).

Notwithstanding these constructive criticisms, the automotive industry is in its infancy with regard the practise of LCA. As recently as 1995, no satisfactory LCA studies had been performed on a car (Allenby and Graedel, 1995). The automotive industry is thus taking constructive steps in adopting this tool and growth in this area is to be encouraged.

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