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A RAPID ASSESSMENT TOOL TO ASSESS FACTORY SUSTAINABILITY

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A RAPID ASSESSMENT TOOL TO ASSESS FACTORY

SUSTAINABILITY

BY

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ABSTRACT

Over the last decades, there has been an increased interest in sustainability and it has become an important issue in production and manufacturing research. To use the traditional definition provided by the Brundtland Commission, sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland p.43). This concept of sustainability might be understood intuitively, but to express and assess specific goals poses an important challenge. As a result sustainability assessment is becoming a rapidly developing area with a growing number of frameworks and tools. However, most of the sustainability assessment tools focus on a national, regional or community level. At this point, the company level has not been considered sufficiently and those tools that are actually used within industry focus mainly on a product level within the organization (Labuschagne et al. 2005). Furthermore, the existing tools require a lot of effort and insight data in order to be completed.

This study presents a tool that overcomes this issues and aims to fill the gap of a missing factory assessment tool. Based on existing integrated sustainability assessment tools a set of indicators is compiled and integrated into a framework that calculates an overall composite index. The developed tool distinguishes itself from other tools, because it is constructed as a user-friendly software that allows the assessment of a factory's overall sustainability with a minimal time effort. It can be used from an external as well as from an internal perspective and considers the differences between industries. Furthermore, it provides the possibility to compare different alternatives and to assess a factory's development over time.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

x

LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
AP	Acidification potential
BAP	Budget Allocation Process
BOD	Benefit-of-the-doubt
CEI	Core Environmental Indicators
CSD	Commission on Sustainable Development
DEA	Data Envelopment Analysis
DJSI	Dow Jones Sustainability Index
EF	Ecological Footprint
EICC	Electronic Industry Code of Conduct
EW	Equal Weighting
FPSI	Ford Product Sustainability Index
GRI	Global Reporting Initiative
GWP	Global warming potential
HDI	Human Development Index
ISO	International Organization for Standardization
LCC	Life-Cycle Costing
OECD	Organization for Economic Cooperation and Development
UN	United Nations
UNCED	United Nations Conference on Environment and Development
VBA	Visual Basic for Applications

LIST OF SYMBOLS

$A_{v,t}$	Quantity of air emissions for period	t-CO$_2$
CE_t	Capital employed for period	million-$
CI	Composite index	
CR	Consistency ratio	
E	Number of employees	
EHS_t	Amount of expenditures on Environment, Health, and Safety compliance for period	million-$
E_t	Energy consumption for period	MWh
F	Number of women	
f_u	Weighting factor of resource	
f_v	Equivalent factor of emission	
FW_t	Quantity of freshwater for period	m^3
HW_t	Amount of hazardous waste for period	Kg
ID_t	Amount of expenditures on staff development for period	million-$
I	Indicator	
$I_{N,i,j}^{-}$	Normalized indicator with negative influence sustainability	
$I_{N,i,j}^{+}$	Normalized indicator with positive influence sustainability	
$I_{i,j}^{-}$	Indicator with negative influence sustainability	
$I_{i,j}^{+}$	Indicator with positive influence sustainability	
IP_t	Amount of expenditures on R&D for period	million-$
$I_{s,j}$	Sustainability sub-index	

J	Dimension	
MA	Number of managers	
$M_{u,t}$	Quantity of resources used for period	Kg
RI	Random matrix consistency index	
$SD_{t,e}$	Quantity of sick days for period	
$SE_{t,s}$	Number of participants in safety trainings for period	
T	Time	
TE_t	Quantity of expenses for period	
TH_t	Quantity of training hours for period	
TR_t	Quantity of revenues for period	
WA_t	Number of workplace related accidents for period	
W_j	Weight factor per indicator	
WL	Wages of lowest wage group	$
W_t	Amount of waste for period	Kg
y_j	Output of a factory	

CHAPTER 1 – INTRODUCTION

This thesis will develop an integrated assessment tool to measure the sustainability of factory related operations. Therefore, the first section of this chapter presents the background of sustainability in manufacturing and the motivation of the thesis. The second part of this chapter describes the objectives of the study and the procedure by which they can be achieved in more detail.

1.1 Background and Motivation

For the last two centuries, industry and economy has evolved on the premise that the earth is an unlimited 'store of resources' and a stable ecosystem (Graedel, Allenby 2010). However, as the population exceeds seven billion and the standards of living improve enormously, the interest and awareness towards the limited natural resources increases as well. The goal is to use the resources consciously in order to satisfy human demand (Davidson et al. 2010). One approach to this challenge can be found in the key concept of sustainability. By regarding the three dimensions: social, environment and economy, it aims for our society to meet present as well as future needs worldwide. Obviously, manufacturing is a major factor in this approach towards a more sustainable society (Despeisse et al. 2012).

Against this background many manufacturing companies have already started to reconsider the idea of being "green" and how to deal with sustainability. However, this change of attitude was of course supported by even more factors. Local environmental regulations have a significant global impact, especially if they are supported by political decisions. Therefore many global manufacturers feared to be locked out of the market, if they do not change their policies towards the concept of sustainability (Srinivasan 2011). Furthermore, investors are also interested in the sustainability performance of

companies and some of them integrated it into their portfolio decisions. They are one of the target groups that use indexes and tools to evaluate companies. This trend towards socially responsible investing is another important factor that forced companies to adapt their strategy (DJSI 2013).

Although rethinking has begun, it is important not to limit the scope of sustainability to the product itself, but to consider the production process as well. There has been a lot of work on researching sustainability on different levels, but sustainability assessment at factory level is still lagging behind (Labuschagne et al. 2005).

1.2   Objectives and Procedure

Against this background the larger goal of the thesis is to focus on sustainability at factory level and to describe the relationship between factories and sustainability dimensions in a basic concept and to develop an integrated assessment tool based on that relationship. In order to achieve this goal, several sub-goals will be pursued during the study. These objectives are summarized below:

- Giving an insight into the history and development of sustainability.
- Reviewing the current state of sustainability assessment tools and categorizing them.
- Examining the impact of factories on their environment and classifying industrial sectors.
- Developing a framework to assess the sustainability performance of factories and to calculate an overall composite index.
- Implementing the model into a computer-based tool by using Visual Basics for Applications.

- Testing the tool by applying an exemplary case study and developing a usability questionnaire.

The procedure which will be performed in this study in order to achieve the set goals is illustrated in the following figure.

Phase	Research Flow	Output
Phase 0 (Chapter 1)	Introduction	
Phase I *Sustainability Assessment* (Chapter 2)	Background on Sustainability / Review on Existing Tools	Categorization of Tools
Phase II *Factory Analysis* (Chapter 3)	Analysis of Factories and their Impact / Classification of Industrial Sectors	Needs for a new Tool / Reduced Set of Sectors
Phase III *Framework Development* (Chapter 4)	Hierarchy Development / Index Model Development	Tool Framework
Phase IV *Tool Implementing* (Chapter 5)	Data Entry Implementation / Data Processing Implementation	Computer-based Tool
Phase V *Tool Validation* (Chapter 6&7)	Exemplary Case Study / Usability Questionnaire	Optimization Potentials

Figure 1.1: Overall procedure of the study

CHAPTER 2 - SUSTAINABILITY ASSESSMENT

In order to develop a new sustainability assessment tool, it is necessary to begin with understanding the background and concept of sustainability and to analyze the state of the art in this field. Therefore, the first section of this chapter will present the basic ideas behind sustainability and its development. In the second section, a comprehensive literature review will categorize existing sustainability frameworks and will identify their characteristics and field of application.

2.1 Basics of Sustainability

Becoming "sustainable" has become central to many aspects of everyday life. Not only does this relate to environmental decisions, but many products, services, production systems and developments now claim to be sustainable. However, in most cases when the term sustainability is used, the definition and the meaning of it are not clear. Sustainability has become a buzzword in the media, and is widely used in a diverse range of contexts with disparate meanings.

2.1.1 Background of Sustainability

Sustainability is derived from two Latin words, *sus* which means up and *tenere*, which means to hold (Theis, Tomkin 2012). After all, the term sustainability is comparatively modern and was hardly used until the 1980s. The timeline in Figure 2.1 illustrates the development.
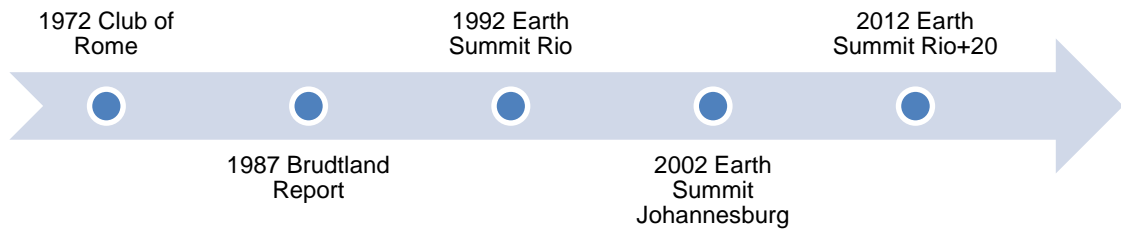
Figure 2.1: Timeline of Sustainability

The first milestone in the history of sustainability was initiated by the Club of Rome and a group of young scientists from the Massachusetts Institute of Technology (MIT). In 1972 they published the controversial report The Limits to Growth, which reported that "the limits to growth on this planet will be reached sometime within the next hundred years". (Donella Meadows, III 1972) This gained enormous media attention and the book became a best seller in several countries. With more than 12 million sold copies and translations into 37 different languages, it is still considered the best-selling environmental book in world history. (Parenti 2012) Sustainability and sustainable development gained further prominence and attention in 1987, when the United Nations' World Commission on Environment and Development published its report *Our Common Future*. The central recommendation of this report, commonly known as the Brundtland report, after the Commission Chair Gro Harlem Brundtland, was to meet the challenges of environmental protection and economic development through a new approach: sustainable development. They defined this development as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". (Brundtland, p.43) This is currently the most quoted definition for sustainability and sustainable development. A milestone towards this goal of sustainable development is characterized by the Rio Earth Summit in 1992, when the United Nations Conference on Environment and Development (UNCED)

agreed on climate change, biodiversity and Agenda 21. In order to supervise and ensure the achievement of these agreements, the Commission on Sustainable Development (CSD) was established. They developed a set of indicators that enabled them to measure sustainable development and provided a basis for decision-making. The CSD meets annually, while the UNCED meets every ten years. Accordingly, the second Earth Summit took place in 2002 in Johannesburg. It focused more on social than on environmental issues. The success of the conference was rather limited, because no important agreements were reached. The last Earth Summit took place in 2012, again in Rio de Janeiro. The outcome document of the conference The Future We Want states all Sustainable Development Goals that the members decided on. (United Nations 2013)

Apart from the CSD, other organizations such as the Global Reporting Initiative (GRI) were founded over the past two decades and they have developed other indicators and matrices to assess sustainability on different levels (more in the following section of the chapter).

2.1.2 Sustainability and Sustainable Development

Acoording to the Brundtland definition of sustainable development, sustainability is a state that will be achieved through sustainable development. Therefore, the literature supports the thesis that both terms can be described and measured as the same and even Agenda 21 uses them interchangeably. (Dresner 2002, p.65) However, this is also the reason why other authors criticize the Brundtland definition. Tim O'Riordan expressed his concerns about the meaninglessness of the term 1988 in his essay *The Politics of Sustainability*. He complains that the formulation is too vague and it allows people to claim everything as being part of the sustainable development

(O'Riordan 1988). Nevertheless, keeping with the common practice, both terms will be used interchangeably in this study.

Besides the definition of sustainable development the Brundtland report contains also two key concepts: "the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs." (Brundtland, p.43) Thus, the report implies that sustainability has three dimensions that it seeks to integrate: economic, environmental and social. Today the common understanding in literature illustrates the three dimensions as overlapping circles as represented in Figure 2.2.

Figure 2.2: Three dimensions of sustainability

This illustration implies that there is an interaction between the different dimensions of sustainability, and progress can be achieved only by considering them simultaneously (Seliger 2007).

2.1.3 Sustainable Manufacturing

Sustainable manufacturing can be considered to be a part of the larger concept, sustainable development. Although it focuses only on one specific aspect, it is still based on the same problems and aims for the same goals.

The most quoted definition is given by the U.S. Department of Commerce. They define sustainable manufacturing as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" (U.S Department of Commerce 2007). This definition demonstrates again the need to consider all three dimensions – economic, social and environmental. Furthermore it also states that sustainable manufacturing includes both the manufacturing of sustainable products as well as the sustainable manufacturing of all products (NACFAM 2009). Therefore, it has to take the entire life-cycle with the stages pre-manufacturing, manufacturing, use and post-use into consideration.

However, with regard to the goal of this study, sustainable manufacturing will be limited to the stage "manufacturing" within the life-cycle and it will focus only on the second part of the statement: sustainable manufacturing of all products.

2.2 Categorization of Sustainability Assessment Tools and Indicators

As mentioned in the previous section, there have been different organizations over the last years that have developed tools and defined frameworks to assess sustainability. The CSD and GRI referred to above are named as two examples. In the literature several authors categorized these tools and frameworks based on numerous factors and dimensions. For example Ness et al. conducted an overview of tools by

considering the focus of the tool (i.e. product level or policy), the temporal characteristics and the degree to which it integrates environmental, social and/or economic aspects (Ness et al. 2007). Feng et al. on the other hand categorized sustainable assessment tools into a hierarchy of global, country, sector, corporation, process, and product levels (Shaw C. Feng et al. 2010). Moreover, Labuschagne et al. conducted an overview of tools that include a set of indicators, integrate all three dimensions of sustainability, have a wide focus and are independent (Labuschagne et al. 2005). This study categorizes tools by considering the following three factors:

- Integration of all three dimensions of sustainability, i.e. if the tool considers environmental, social and economic aspects.

- The hierarchy/focus, i.e. if the focus is at the global, country, sector, corporation or product level.

- Developed by a company or by an organization

The developed categorization and overview of sustainability assessment tools is illustrated in Figure 2.3. It consists of two main branches; the non-integrated and the integrated indicators. The non-integrated indicators include indicators that do not consider all three dimensions of sustainability simultaneously. Therefore, they are further broken down into development, economy based and eco-system based indices. The second branch on the other hand covers all integrated tools and divides them first into macro and micro tools and subsequently into a hierarchy of global, country, sector, corporate and product level. While the macro tools are developed by superordinate organizations, the micro tools are developed by a company. This separation is based on the main issue of macro frameworks and tools. Their focus is mainly "on the external reporting for stakeholders, rather than on internal information need to decision-making and re-design or optimization for actual eco-innovation." (Shaw C. Feng 2009, p.2).

The tools developed by a company (micro tools) on the other hand give the manufacturers the possibility to evaluate and track their sustainability performance within the environment they are in. But the issue with those tools can be seen in the fact that they are designed mainly for the specific environment of a company or supply chain. Therefore it is important to include both in the overview.
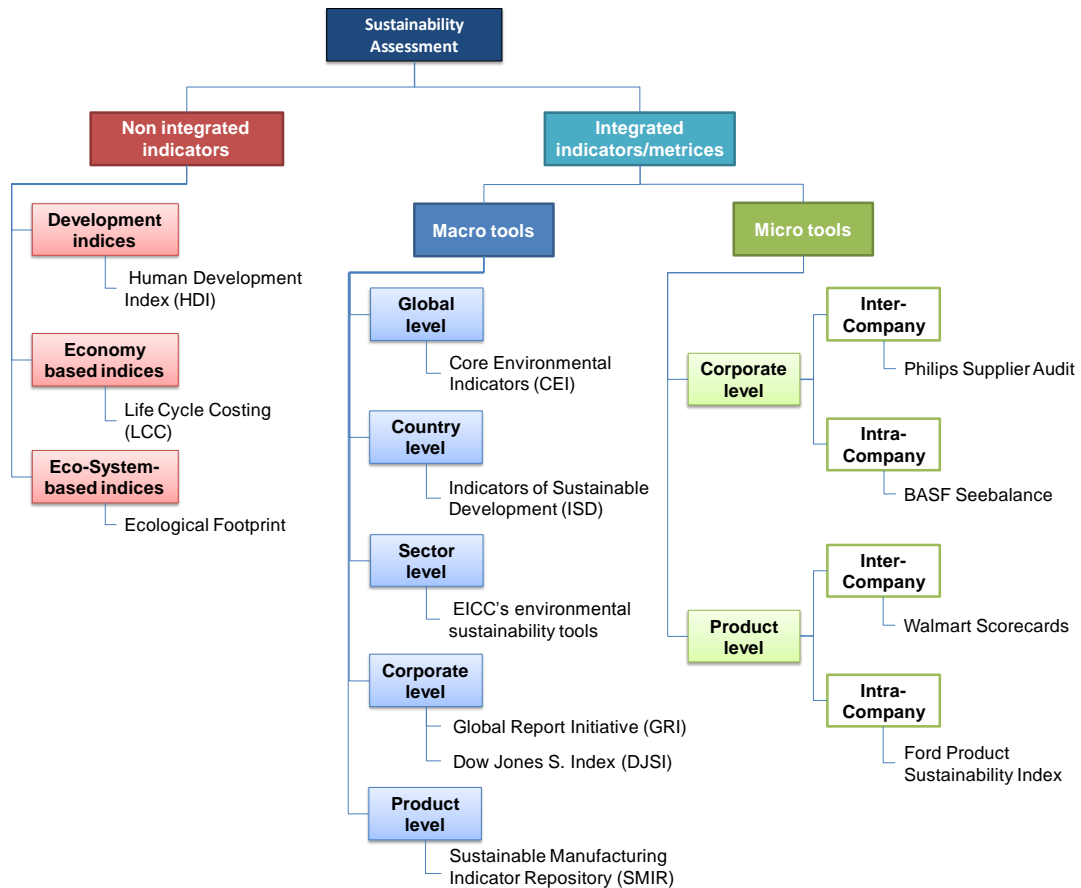
Figure 2.3: Categorization of assessment tools

2.2.1 Review of Current Non-Integrated Indicators

Non-integrated indicators include all indices that do not consider the three traditional dimensions simultaneously. Therefore, they are divided into three different levels (see Figure 2.3). The development indices focus mainly on the social dimension,

while the economy based indices focus on the economy and the eco-system based indices on the environmental dimension. In the following the most quoted indicator at each level will be described briefly.

Development Indices

The best known indicator at this level is the *Human Development Index* (HDI) developed by the United Nations. This indicator consists of three main components. The education component measures the mean years of schooling against the expected years of schooling. The health component on the other hand is measured based on the life expectancy at birth and a third component measures the gross national income per capita to express the living standard. Additionally, all components are evaluated based on a minimum and a maximum value and then normalized. (UNDP 2013)

Economy based Indices

At this level, *Life-Cycle Costing* (LCC) is one of the most important methods. It is an economic approach to get the total cost of goods by examining all the parts of the cost over its lifetime. This includes costs for research and development, production, maintenance and disposal. Thereby, Life-Cycle Costing is not associated with environmental costs, but with costs in general. Overall, it is an important tool to support decision making. (Gluch, Baumann 2004)

Eco-System based Indices

At the eco-system based level, the *Ecological Footprint* (EF) is one of the most quoted indicators. The Ecological Footprint developed by Wackernagel and Rees (Wackernagel, Rees 1996) is defined as the quantitative land area on earth that is required to sustain the given living standard until infinity. This includes also areas, which are needed to produce food and clothes or to supply energy. Moreover, it takes also

the waste assimilation requirements in terms of a corresponding land area into account. Finally, the result is expressed per hectare per person and year. In other words, "EF analysis is an accounting tool that enables us to estimate the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area" (Wackernagel, Rees 1996, p.9).

2.2.2   Review of Current Integrated Tools

In contrast to the non-integrated indicators, the integrated tools are characterized by the fact that they consider the three traditional dimensions of sustainability at the same time. Generally, all of these tools follow the same structure, which is illustrated in the following figure.
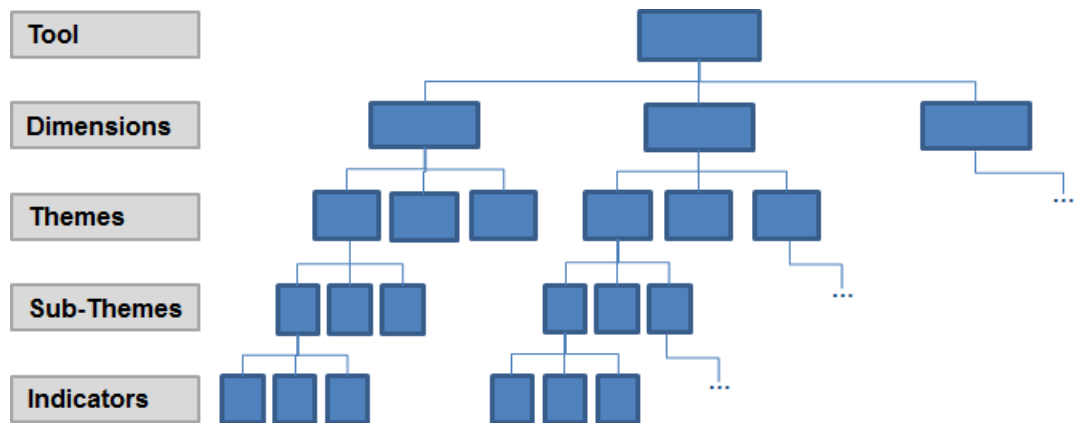
Figure 2.4: Hierarchical structure of sustainability assessment tools

At the highest level the tool is divided into dimensions and subsequently divided into different themes and sub-themes. At the lowest level of the hierarchy are the sustainability performance indicators.

After a thorough literature analyses the most quoted and relevant integrated sustainability assessment tools will be described in the following, including the first three levels of their frameworks: tool, dimensions and themes (see Figure 2.4).

Global level

At the global level, the *Core Environmental Indicators* (CEI) developed by the Organization for Economic Co-operation and Development (OECD) are considered to be the most relevant indicators. They can be used to measure environmental performance, to report on the progress towards sustainable development and also to monitor the integration of economic and environmental decision making as well as society's response (OECD 2001, 2003). The core set contains about 50 indicators with a strong focus on environmental issues, but it integrates also society and economic aspects (OECD 2001). The hierarchical structure is shown in Figure 2.5.
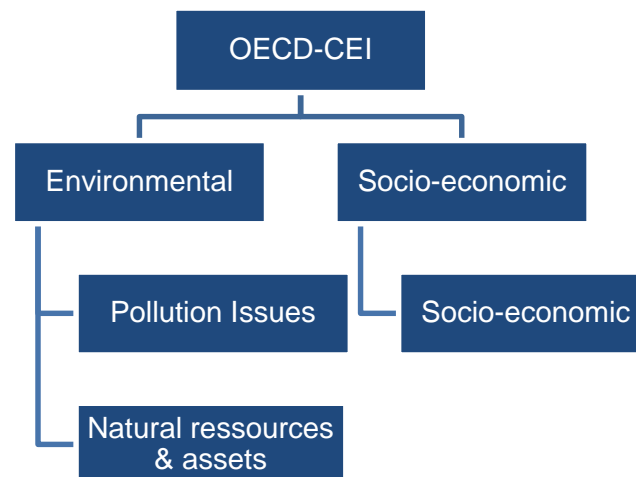
Figure 2.5: Hierarchical structure of the OECD-CEI

Country level

At the country level, the *UN commission's sustainable development group* (UN-CSD) has developed another hierarchical framework for the evaluation of sustainability.

The background that led to the development of this tool is described in chapter 2.1.1.

The latest version of the framework consists of 44 subthemes, 14 main themes and four main areas. In contrast to the traditional view of three dimensions, the UN-CSD considers institutional aspects as an additional main area. However, in the newly revised set the division along the main areas is no longer explicit, because the framework aims to integrate the main areas with cross-cutting themes like poverty or natural hazards (United Nations 2007). The main themes covered by the framework are illustrated in Figure 2.6. Overall, these indicators measure sustainable development mainly from a society or national perspective and therefore not all of them are relevant to industrial and business organizations (Labuschagne et al. 2005)
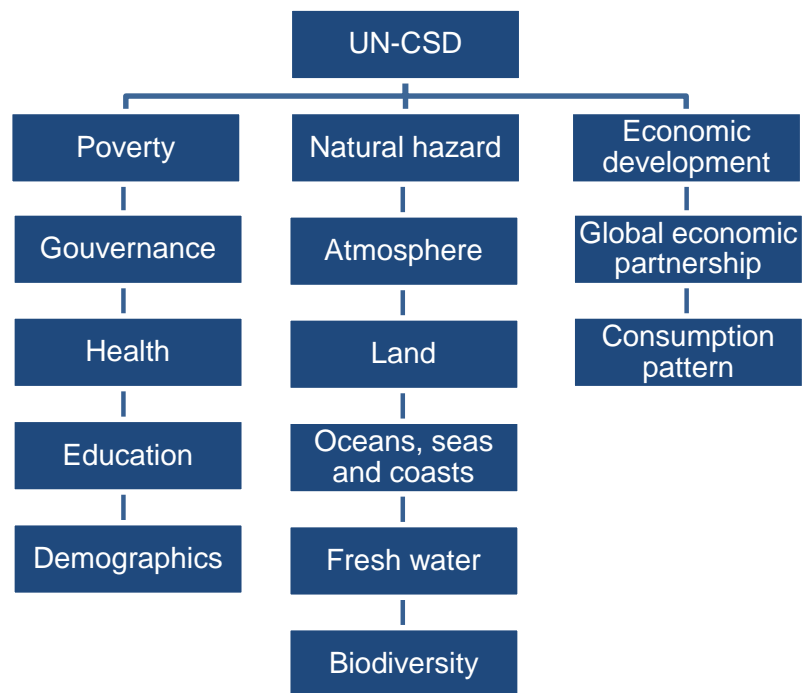
Figure 2.6: Hierarchical structure of the UN-CSD

Sector level

At the sector level, the electronic sector can be considered as a pioneer and good example when it comes to sustainability. The Electronic Industry Citizenship Coalition

released the *Electronic Industry Code of Conduct* (EICC code) in 2004. The EICC code provides guidelines on social, environmental and ethical aspects through five main themes (see Figure 2.7) that may be integrated and adopted by the companies on a voluntary basis. So far more than 40 world-leading companies like Cisco, Philipp and Apple support the EICC code and have also introduced it to their suppliers. (EICC 2012)
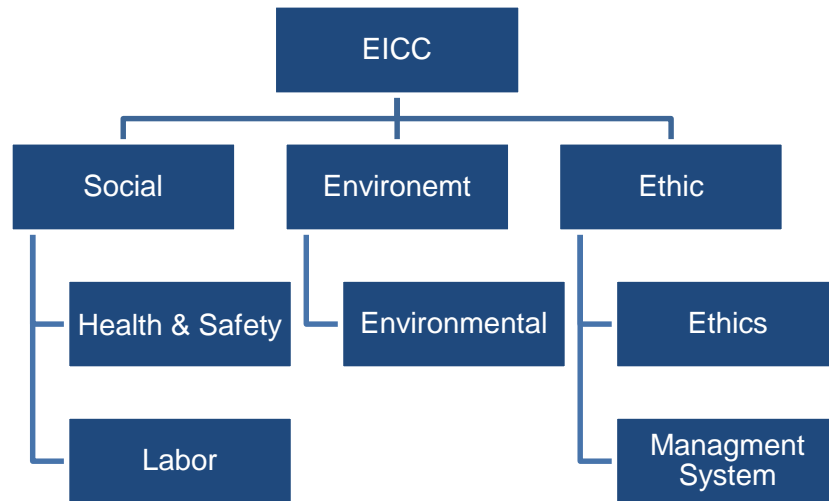
Figure 2.7: Hierarchical structure of the EICC code

Corporate level

With the regard to the goal of the study, to assess factory sustainability, the corporate level is considered to be the most important hierarchical level. It also includes factories as an aspect. Therefore, it is important not only to focus on one tool, but to describe this level extensively.

One of the most quoted tools on this level is the *Global Reporting Initiative* (GRI). The GRI was launched in 1997 by the United Nations Environment Program (UNEP) together with the US non-profit organization the Coalition for Environmentally Responsible Economics (CERES). It is designed to be used by organizations of any size, sector or location and to report on sustainability of the entire organization.

Therefore, the GRI uses a hierarchical framework in three focus areas. The social focus area concerns the impacts an organization has on the social system within which it operates. It includes indicators surrounding labor practices, human rights, society and product sustainability at all company locations. Environmental indicators on the other hand take inputs like materials, water and energy as well as outputs like emissions, effluents and waste into account. Additionally, the economic indicators of sustainability illustrate the organization's main economic impact on stakeholders and throughout society. The hierarchical structure is demonstrated in Figure 2.8. Overall, the guideline contains 84 indicators, but only few organizations provide detailed information on all focus areas or evaluate all indicators (Global Reporting Initiative 2011; Labuschagne et al. 2005; Hussey et al. 2001)
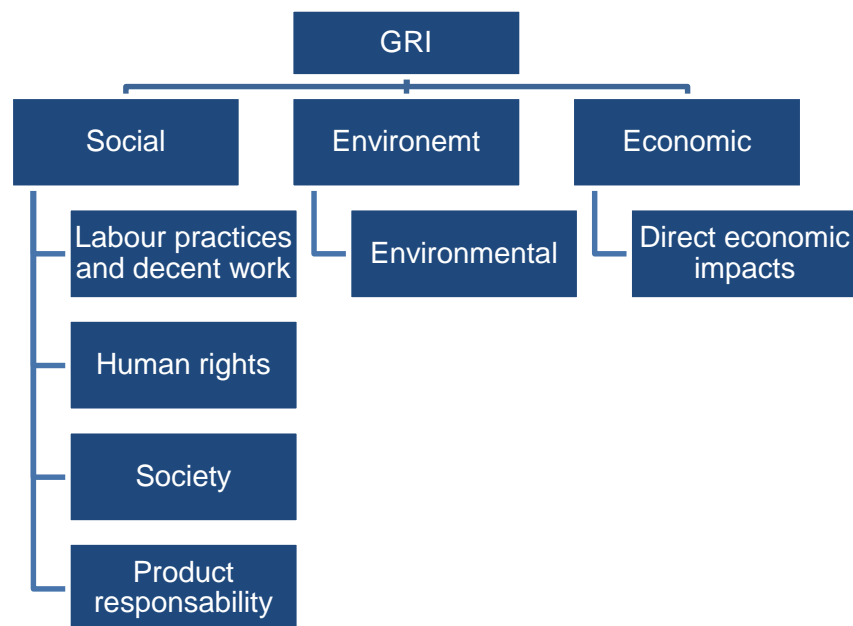
Figure 2.8: Hierarchical structure of the GRI

The *Dow Jones Sustainability Index* (DJSI) is another important tool on this subject. It was launched in 1999 by Dow Jones Indexes and the company SAM as the first global sustainability benchmark. The DJSI evaluates the sustainability

performance of the world's leading companies in terms of economic, environment and social themes (see Figure 2.9). It is a weighted set of general and industry-specific criteria, according to which the companies are ranked within their industry. Only the leading company in each industry is selected for the DJSI. This tool is used especially as benchmarks by investors who integrate sustainability consideration into their portfolio and support sustainable investment. (DJSI 2013)

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                          ┌──────────┐
                          │   DJSI   │
                          └────┬─────┘
        ┌──────────────────────┼──────────────────────┐
   ┌─────────┐          ┌─────────────┐          ┌─────────────┐
   │ Social  │          │  Environemt │          │  Economic   │
   └────┬────┘          └──────┬──────┘          └──────┬──────┘
        │                      │                         │
  ┌──────────────┐     ┌──────────────┐          ┌──────────────┐
  │Social        │     │ Biodiversity │          │ Brand        │
  │reporting     │     │              │          │ management   │
  └──────────────┘     └──────────────┘          └──────────────┘
  ┌──────────────┐     ┌──────────────┐          ┌──────────────┐
  │Stakeholder   │     │Climate       │          │Stakeholder   │
  │engagement    │     │strategy      │          │engagement    │
  └──────────────┘     └──────────────┘          └──────────────┘
  ┌──────────────┐     ┌──────────────┐          ┌──────────────┐
  │Additional    │     │Additional    │          │Additional    │
  │items         │     │items         │          │items         │
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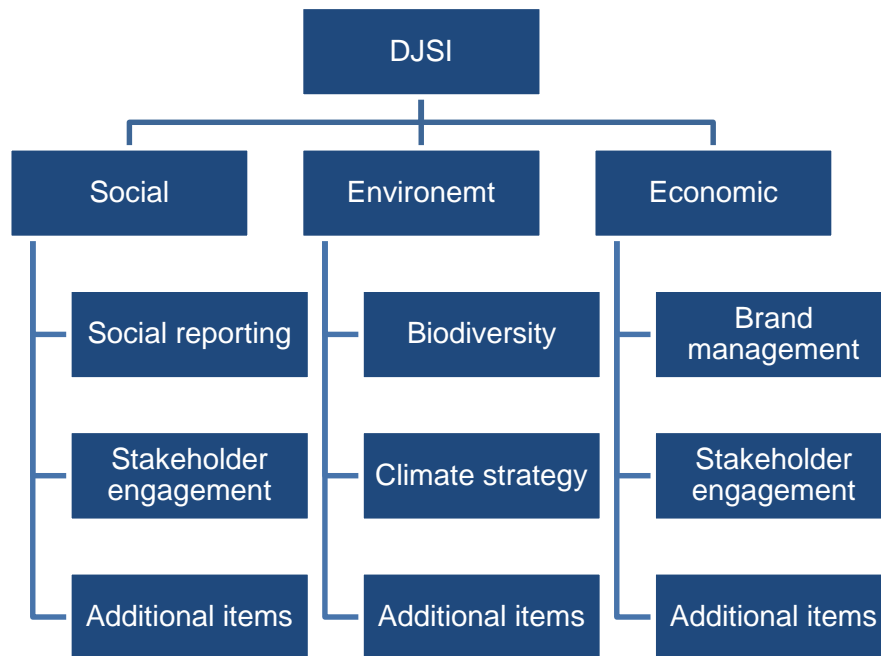
Figure 2.9: Hierarchical structure of the DJSI

In contrast to the GRI and Dow Jones Sustainability Index, *BASF Seebalance* is developed by a company and not by a superordinate organization. With regard to the categorization in Figure 2.3, it is considered to be a micro-tool. Initially BASF, the world's leading chemical company, has developed the eco-efficiency analysis to assess environmental and economic opportunities and risks in any business activities. Based on this two dimensional approach (environment and economic), BASF created the socio-eco-efficiency analysis, known as Seebalance by also integrating the third dimension (social) (Uhlman, Saling 2010). The socio-eco-efficiency analysis involves

measuring the environmental impact over its entire lifecycle. It measures at least eleven environmental impacts in six main themes (see Figure 2.10). The results are then aggregated using weighting schemes for each category. Another aspect of the Seebalance concerns the full economic impact of all alternatives, in order to determine an overall total cost of ownership. All identified costs are summed, normalized and combined in appropriate units, without weighting them. Finally, the socio-eco-efficiency analysis assesses also the social fingerprint. Therefore, it takes five themes into account and weights them. The themes are shown in Figure 2.10. Overall, this tool allows it to quantify sustainability for different alternatives and to compare them. Therefore, it is useful for supporting strategic decision-making, marketing and also for prioritizing R&D activities (Saling et al. 2005).
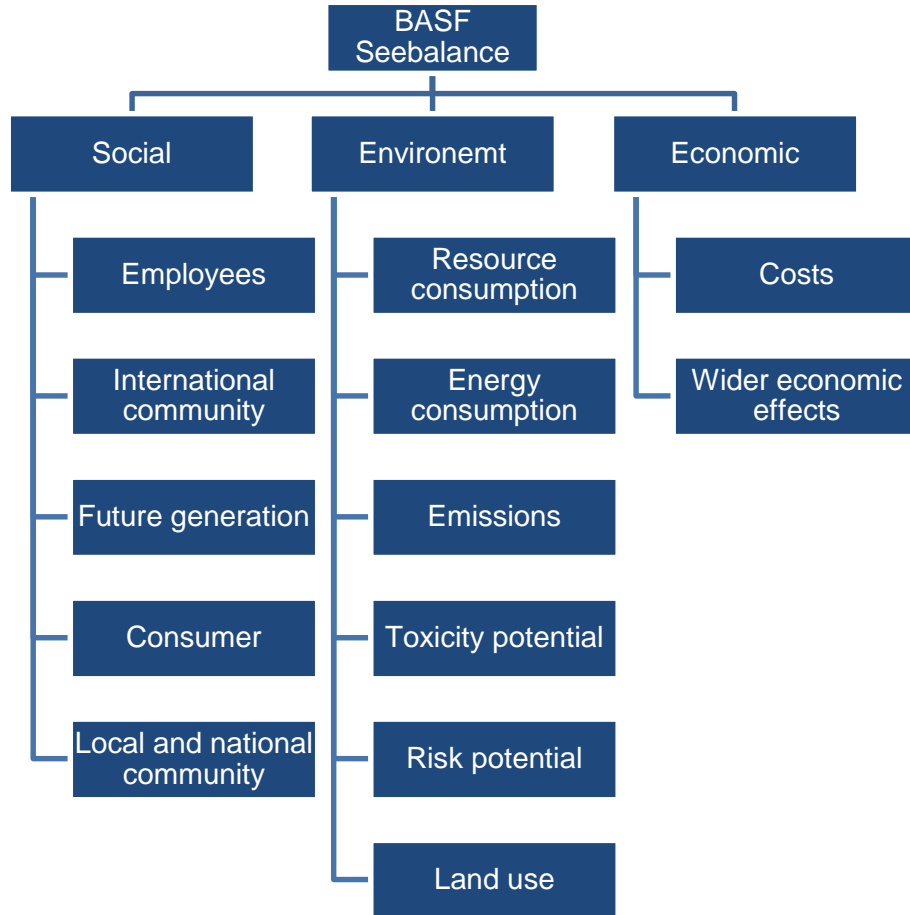
Figure 2.10: Hierarchical structure of the BASF Seebalance

Product level

Like the BASF Seebalance, the *Ford Product Sustainability Index* (FPSI) is also considered to be a micro-tool. It is directly used by Ford's engineers to improve the sustainability performance of the products and not to report to a superordinate organization. The tool looks at eight different indicators, reflecting key impacts of automotive products. The dimensions and themes are illustrated in Figure 2.11. Since the tool focuses on only few key elements with available data, the effort to complete the tool is rather easy and it can be done in approximately 10 – 15 hours for the whole product development process. The tool has been applied the first time for the vehicles

Ford Galaxy and S-MAX and resulted in a significant improvement of the sustainability performance (Schmidt 2006).
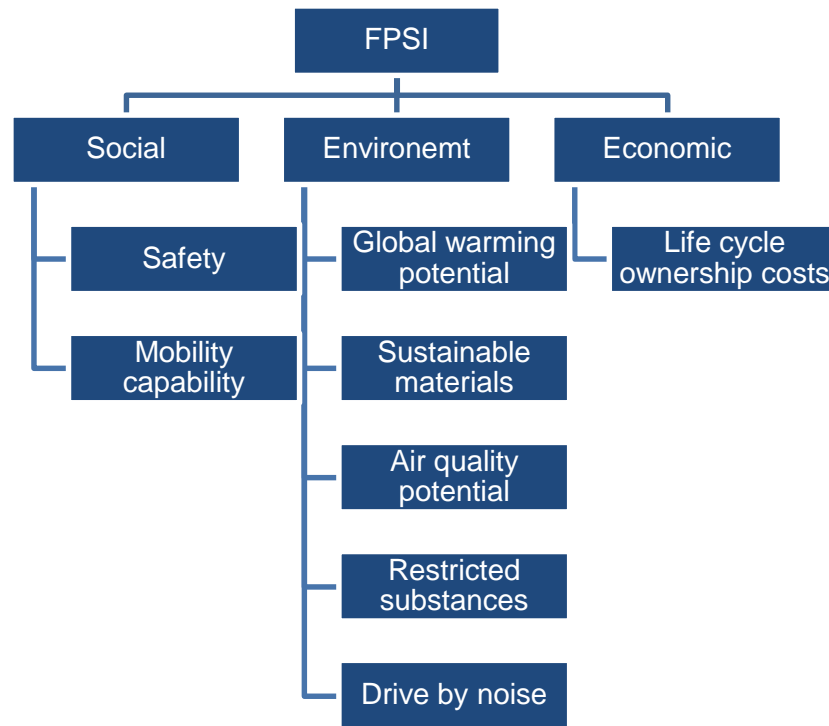
Figure 2.11:   Hierarchical structure of the Ford PSI

Another framework at this level was created by the company Wal-Mart. In contrast to Ford's approach, Wal-Mart designed their tool to be used not only within the company, but mainly from their suppliers. For this reason it is considered to be at the inter-company level. As one of the worldwide leading retailers, Wal-Mart was accused of unfavorable business practices with a significant ecological impact and high carbon footprints. Therefore, they changed their mission towards a sustainable development and implemented an environmental initiative. (Nandagopal, Sankar 2009) Wal-Mart expresses this mission through three goals: to be supplied 100% by renewable energy, to create zero waste and to sell products that sustain people and the environment (Wal-Mart 2012). In order to accomplish these goals Wal-Mart focuses on its suppliers and especially on the product packaging. In 2006, they released a packaging scorecard

with the intention of helping suppliers to improve packaging sustainability and to conserve resources. This scorecard is a measurement tool that allows the suppliers to evaluate themselves relative to other suppliers. The evaluation is performed using a specific metric which is based on the "7 R's of Packaging": Remove, Reduce, Reuse, Recycle, Renew, Revenue, and Read. (Wal-Mart 2006; Zettlemoyer 2007) The themes are shown in Figure 2.12.
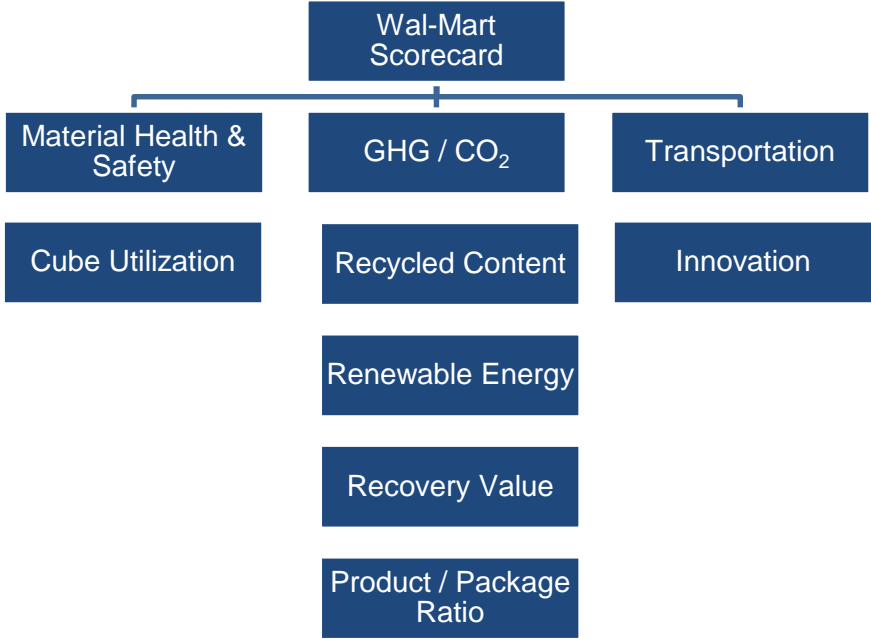
Figure 2.12: Hierarchical structure of the Wal-Mart Scorecard

CHAPTER 3 - FACTORIES AND INDUSTRIAL SECTORS

Since the thesis develops a tool to assess *factory sustainability*, it is important not only to look at the sustainability aspect, but also at the factory aspect. Therefore, this chapter presents a basic description of factories and illustrates their importance in terms of sustainability, based on energy use and CO_2 emissions. Besides the influence of general factories, the industry specific influence by sector is also considered. Finally, the chapter concludes with explaining the need for a factory specific sustainability assessment tool that will be developed in the next chapters.

3.1 Basics of Factories

The term factory is derived from the Latin word *facrica*, which means workshop. Generally, a factory describes a place where added value takes place by manufacturing industrial goods using factors of production (Klemke et al. 2010). In contrast to traditional craft workshops, industrial factories are highly complex socio-technical systems that cannot be generalized easily. The whole factory consists of different levels which are ranked in a hierarchal order. Two of the main orders and views are described by Westkämpfer and Wiendahl. Both views of a factory are shown in Figure 3.1.
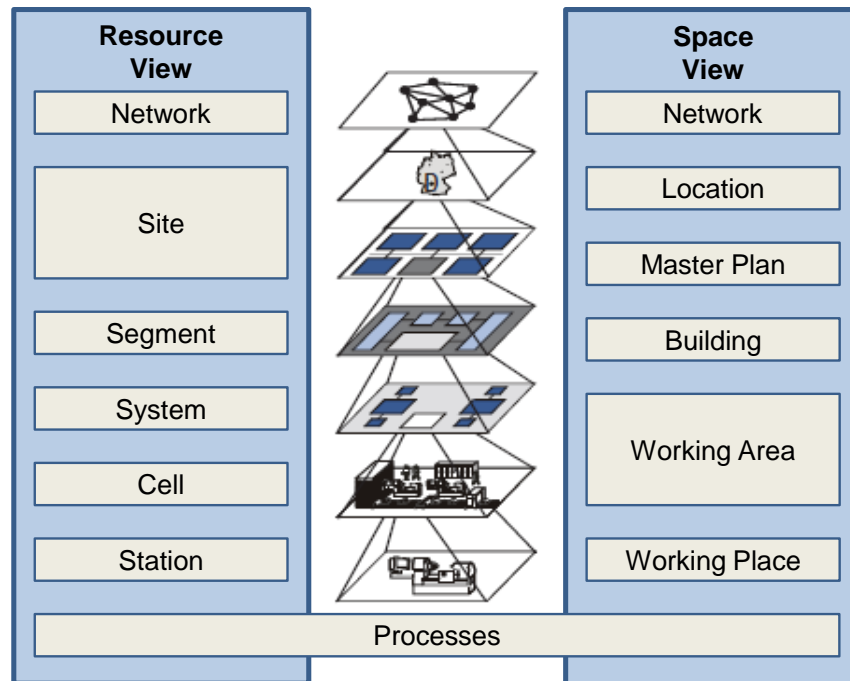
Figure 3.1: Structuring levels and views of a factory based on (Wiendahl et al. 2007)

Both structures subdivide factories into seven levels and consider *network* to be the highest and *processes* to be the lowest level. Nevertheless, the interpretation of the levels differs depending on the view. The *resource view* by Westkämpfer divides the levels with a focus on technical and human resources, whereas the *space view* by Wiendahl considers primarily the space that will be needed by the resources (Wiendahl et al. 2007).

Moreover, it is important to classify factories also in an overall system. For this purpose, different descriptive models have been developed. In terms of sustainability the life cycle assessment appears to be the most relevant approach, where factories are considered to be a stage in the product life cycle. This approach attempts to evaluate the environmental impact of products throughout the entire life cycle of a product from raw material extraction, manufacturing, and use to ultimate disposal (see Figure 3.2) (Satish Joshi 2000).
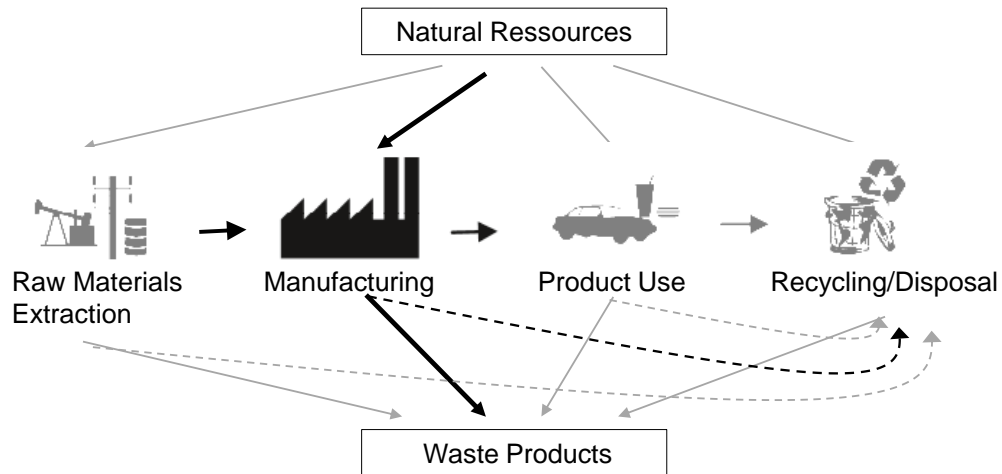
Figure 3.2: Factories within the product life cycle based on (Wiendahl et al. 2007)

Figure 3.2 illustrates the entire product life cycle, but focuses on the environmental impact of factories. It demonstrates that factories influence the environment by using natural resources like water and air, as well as by creating waste products. Furthermore, it takes the *ecological backpack* of input products into account and also the environmental impact of the output products (Müller et al. 2009).

This section of the chapter gives a rough impression about the complexity and significance of factories, based on the hierarchical order and the entire product life cycle. However, in the following course of the study it is necessary to reduce the complexity and to limit the scope in order to create a rapid assessment tool. Therefore the factory will be considered in its entirety and the pre- and post-stages of the factory will not be taken into account.

3.2 Impact of Factories on their Environment

The previous section of the chapter has already indicated that the manufacturing industry produces adverse environmental impacts such as waste generation and consumption of natural resources. The significance of factories becomes particularly

obvious by regarding the global energy use. In 2004 the total global primary energy supply was about 469 exajoules (EJ). With 113 EJ the manufacturing industry accounts for nearly one third of this energy use. Even though the industrial energy intensity (energy use per unit of industrial output) decreased over the last decades across all manufacturing sectors, the absolute energy use has increased (OECD Sustainable Development Studies). In total it even increased by 61% between 1971 and 2004. This development is illustrated in Figure 3.3.
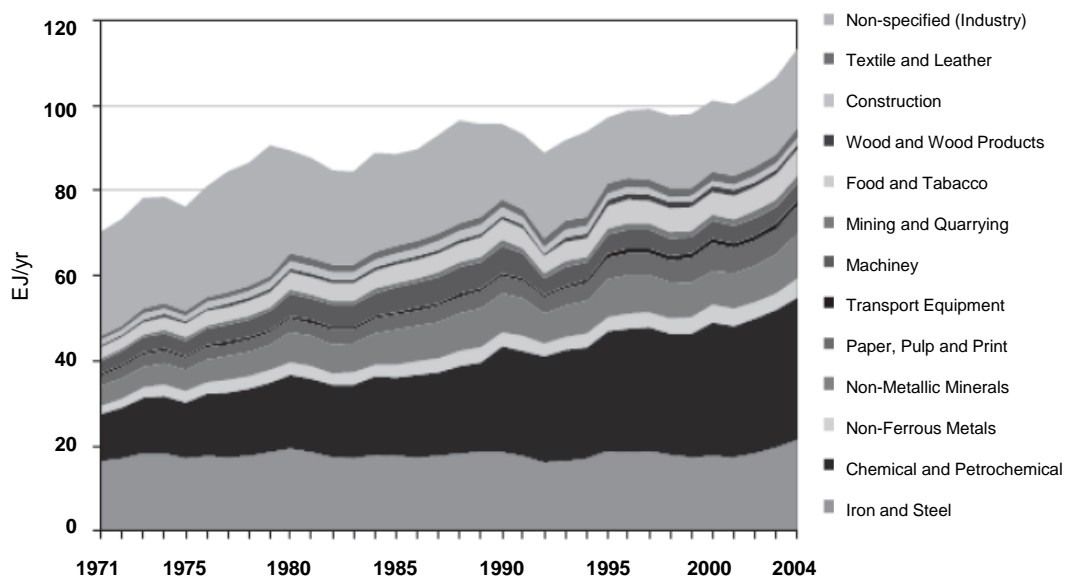
Figure 3.3: Global Industrial Energy Use, 1971 – 2004 (OECD Sustainable Development Studies)

Furthermore, Figure 3.3 shows that the energy consumption depends highly on the industrial sector. Raw material productions such as chemical and petrochemicals, iron and steel, non-metallic minerals and non-ferrous metals consume most of the industrial energy. The chemical and petrochemical sector alone accounts already for 30% of industrial energy use.

Regarding CO_2 emissions similar conclusions can be observed. With 9.7 gigatonnes (Gt) in 2004, the manufacturing industry accounts for 36% of total CO_2

emissions (OECD Sustainable Development Studies). The figure below demonstrates that like industrial energy use, CO_2 emissions vary as well depending on the sector. In 2004 the three sectors Iron & Steel, Non-Metallic Minerals and Chemical & Petrochemicals account for 70% of industrial CO_2 emissions.
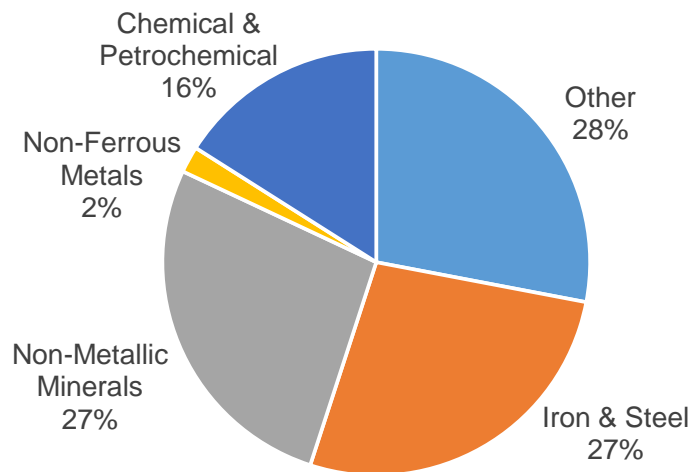
Figure 3.4: Industrial Direct CO2 Emissions by Sector, 2004 (OECD Sustainable Development Studies)

Besides the industrial energy use and industrial CO_2 emissions, the significance of factories is also shown by regarding the general pollution. According to the European Environment Agency (EEA) "manufacturing contributes 22% of European global warming potential as well as 14% of acidification potential, and 21% of tropospheric ozone potential" (OECD Sustainable Development Studies, p. 65).

So far, only air pollution and energy consumption have been considered for describing the relationship between manufacturing and sustainability. Nevertheless, there are even more issues, which indicate that sustainable manufacturing will become one of the major objectives within industry in the twenty-first century. Not only

improvements in efficiency and reductions on pollution have to be made but also traditional paradigms for doing business have to be changed.

3.3   Classification of Industrial Sectors

As the section above has already indicated, the different industrial sectors need to be considered. Depending on the sector the consumption of energy, CO_2 emissions and general air pollution varies significantly. But not only environmental indicators are influenced by sectors, the social and economic indicators are affected as well. The Dow Jones Sustainability Index for example weights the social indicator *Occupational Health and Safety* especially high for (raw) material sectors such as steel or oil. The economic indicator *Corporate Governance* on the other hand is considered to be very important for the automotive sector (SAM 2013).

Based on the explained significance of industrial sectors it is necessary to divide the manufacturing industry into sectors within this study as well. The indicators need to be weighted sector-specifically in order to receive a meaningful sustainability score. The figure below presents the classification of different sectors.
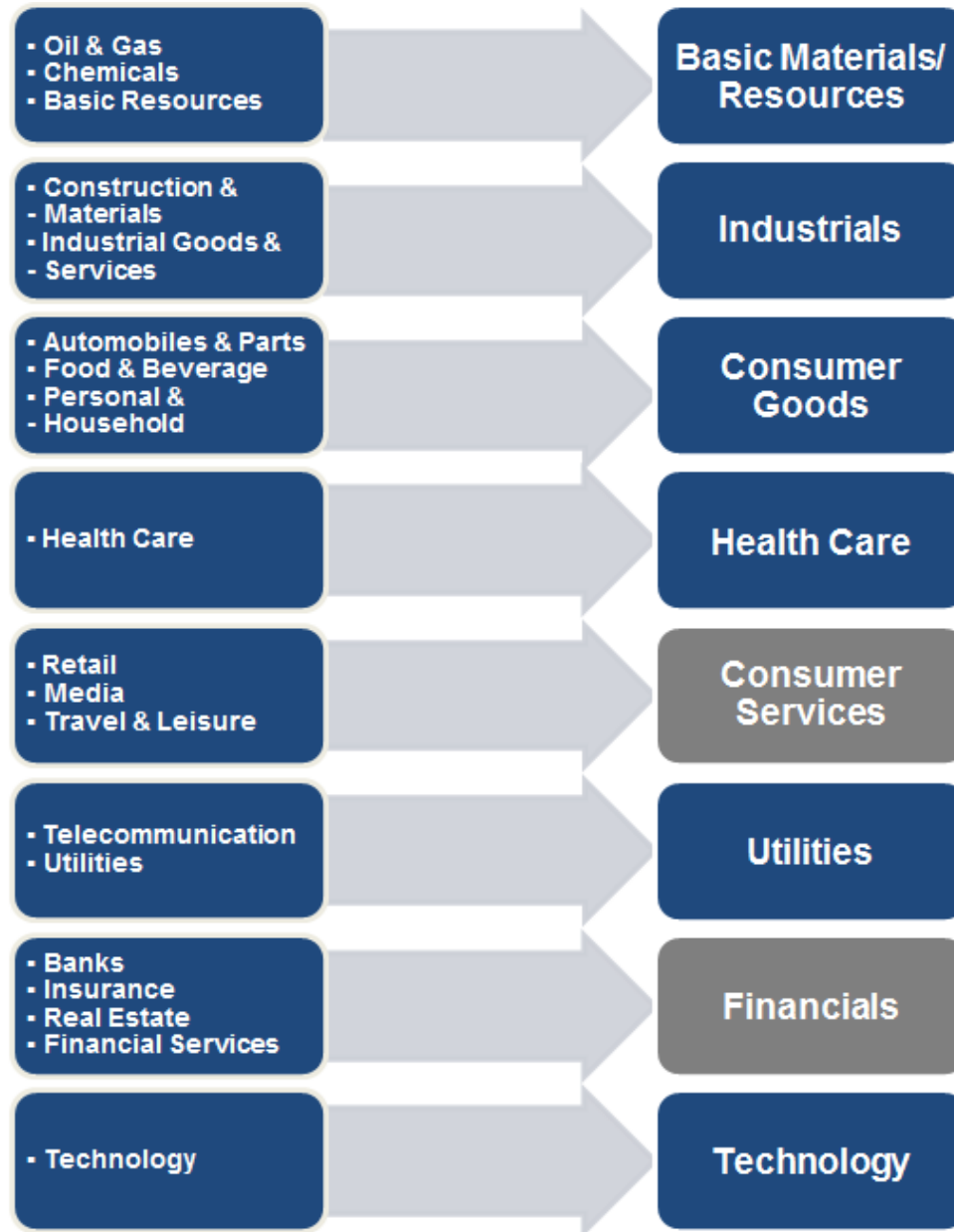
Figure 3.5: Classification of industrial sectors

The left side of Figure 3.5 lists the 19 supersectors that are used by the DJSI. However, their classification is not suitable for this study. In order to reduce the complexity it is necessary to combine some of the supersectors. Hence the right side of the figure presents the results of the combination. Moreover, only factory related sectors are relevant for this work. Since the sectors *Financials* and *Consumer Services*

do not operate with factories they will not be considered any further. As a result six main sectors: *Basic Materials, Industrials, Consumer Goods, Health Care, Utilities* and *Technology* remain.

3.4 Needs of an Individual Tool at Factory-Level

This chapter demonstrates that the manufacturing industry is a main consumer of natural resources and a main producer of adverse environmental impacts. It signifies that there is a high responsibility of factories towards their environment. For this reason it is important to design a tool for the sustainability evaluation of factories. Although the purpose of such a tool is primarily to assess the sustainability performance of the factory, it can also guide factory managers to think and act in the right direction and to discover possible improvements in order to increase the sustainability metrics related to factory operations.

Even though the literature review from chapter 2 indicates that several frameworks and tools are already available to assess sustainability, it also demonstrates that they vary depending on the subject of investigation and it needs a lot of insight knowledge and effort to use those tools. Moreover, current tools focus primarily on regional, national and global levels. At this point, the company level has not been considered sufficiently and those tools that are actually used within industry focus mainly on a product level within the organization (Labuschagne et al. 2005).

CHAPTER 4 – DEVELOPMENT OF A FRAMEWORK

In order to fill the gap of a missing factory assessment tool it is necessary to develop effective sustainability indicators and a reasonable framework. Therefore, it is important to specify the purpose of the tool in the beginning. This chapter presents general criteria for indicators and also specific criteria for each dimension of sustainability: social, environmental, and economic. Based on those criteria appropriate indicators are derived in the next step for each dimension. The derived indicators are then judged as to whether an indicator supports or harms a company's sustainability. The next step requires a normalization of the indicators to avoid adding up incompatible data sets that can lead to inaccuracies in future steps. After evaluating and normalizing the indicators, they also have to be weighted based on the type of industry in order to obtain a meaningful evaluation of the sustainability performance of factories within each industry. From this model it is possible to calculate a sub-index for each sustainability dimension. Finally, all three sub-indices are combined into one overall composite sustainable performance index. The figure below visualizes the process.
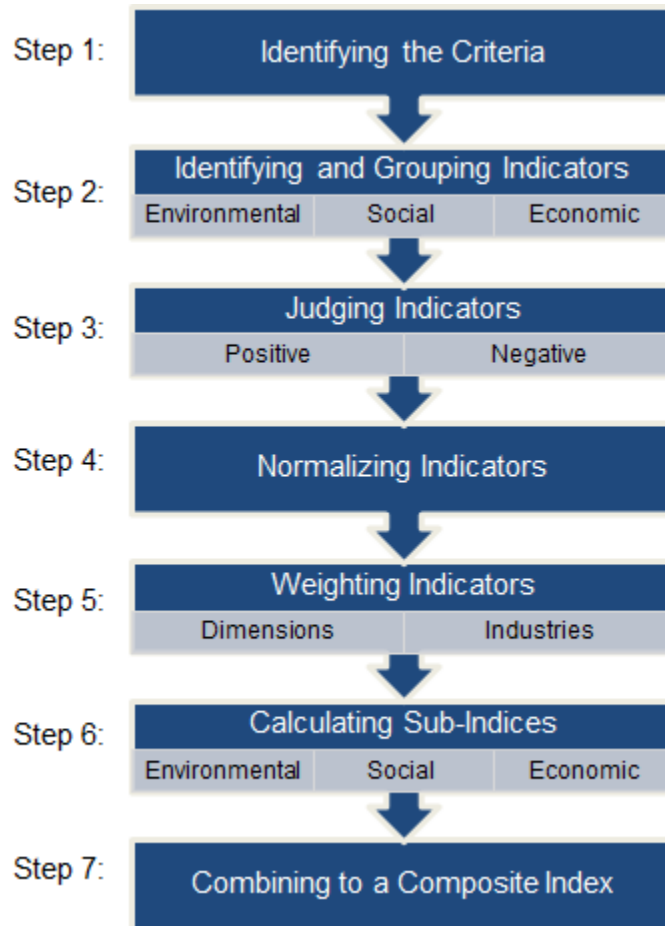
Figure 4.1: Methodology for developing a framework to assess factory sustainability

4.1 Purpose of the Tool

Generally, the study aims to develop a tool that assesses a factory's sustainability performance. Furthermore, it is the goal to ensure a rapid and integrated assessment for all industries. Besides these general characteristics, the tool also has to meet specific criteria listed below, which distinguish it from other tools.

- It should be possible to use the tool as an external user without internal information. That means the data for the indicators should be available through published sustainability reports, webpages etc.

- It should be possible to evaluate a single factory.

- It should be possible to evaluate two or more factories and assess them as alternatives against each other.

- It should be possible to evaluate one factory over time, in order to observe its sustainable development.

Based on the integration of these criteria the tool's purpose is intended for external investors as main users who integrate sustainability consideration into their portfolio. The tool provides a quick and general overview of the sustainability performance and supports the comparison of different alternatives. At the same time internal factory managers may also use the tool to compare themselves to other companies or to identify possible improvements or deteriorations in terms of sustainability.

4.2   Criteria of Sustainability Performance Indicators

Indicators are simple measures; most often quantitative that represent a state or condition of something. An example of an indicator is a thermostat displaying 32 degrees. In this sense, indicators typically provide key information about a physical, social, or economic system and also allow analyzing trends and relationships. Thus, indicators are usually a step beyond primary data (Veleva, Ellenbecker 2001). They vary depending on the type of system they monitor. In terms of this study, sustainability indicators can be defined as "information used to measure and motivate progress toward sustainable goals" (Ranganathan 1988, p.2). However, there are certain characteristics that effective sustainability indicators have in common. The Sustainable Measures Group (Sustainable Measures 2010) as well as Anderson et al. and Feng et al. (Feng et al. 2010) have established the following criteria:

- *Measurable*: Indicators need to be capable of being measured quantitatively or qualitatively.

- *Relevant*: Indicators have to fit the purpose of measuring sustainability performance and provide useful information on it.

- *Understandable*: Indicators should be easily understood by people who are not experts.

- *Manageable*: Indicators have to be limited to the minimal number required, to meet the purpose of measuring.

- *Reliable*: Indicators need to provide trustworthy information.

- *Data accessible*: Indicators have to be based on information that are available or can be easily accessed.

- *Timely manner*: Indicators should be measured on a regular basis to enable timely, informative decision-making.

Besides those characteristics regarding the content of indicators, there are further attributes regarding the format and structure of indicators (Joung et al. 2013; Veleva, Ellenbecker 2001):

- *Identification:* Indicators should be organized either alphabetically or numerically.

- *Name:* Indicators need to be clearly designated.

- *Definition:* Indicators should be defined with their essential characteristics and functions.

- *Unit of measurement:* The value of indicators has needs to be specified (e.g. kilograms, tons, percent, hours)

- *Type of measurement:* Indicators can be measured either quantitatively or qualitatively and further can be either absolute (e.g. total energy used per year) or adjusted (e.g. energy used per unit of product per year)

- *Period of measurement:* Indicators have to be measured over a defined period of time (e.g. year, quarter, month)

The characteristics listed above help to distinguish indicators from primary data, goals, parameters, or issues. The following example demonstrates the importance. "Using renewable energy" is often labeled as a sustainability indicator by the media, even though it is not. In fact, it is a goal. In order to define an indicator it is necessary to consider all the mentioned characteristics. In terms of renewable energy use a possible indicator would be "percent of energy from renewables, measured at a facility over a period of one year" (Veleva, Ellenbecker 2001).

4.3   Identifying and Grouping of Sustainability Performance Indicators

In order to identify and group indicators it is necessary to define a hierarchical structure for the framework. Figure 2.4 illustrates the general hierarchy for integrated sustainability tools. However, to suit the needs of the tool developed within the study, it has to be modified and adapted for factories. The following figure presents the new structure, including the modifications.
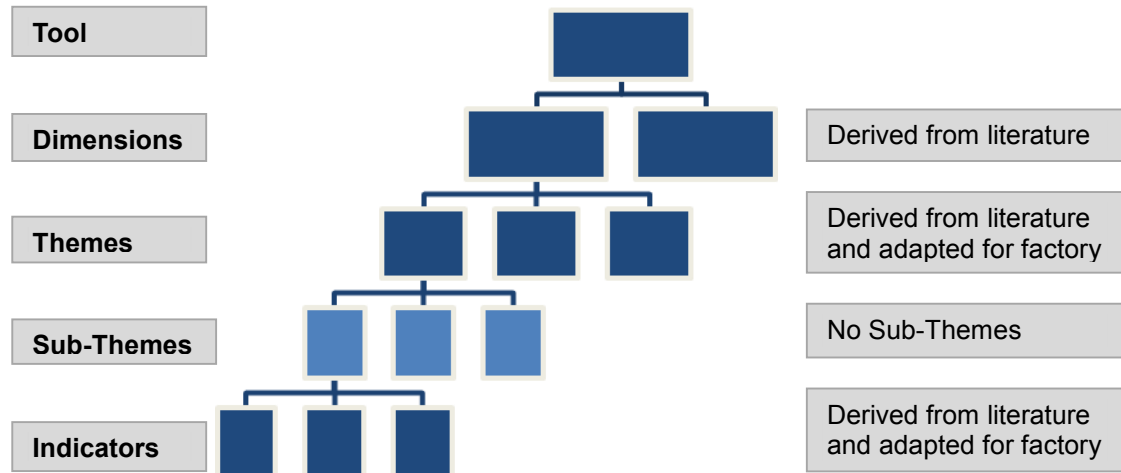
Figure 4.2: Structure of the Factory Sustainability Framework

According to this figure, the dimensions are derived from the literature. This can be done easily, because the general literature focuses on the three traditional dimensions of sustainability: social, environment and economy (see chapter 2). Therefore, the framework adopts this view and contains the same three dimensions.

In contrast to the dimensions, the themes and indicators require more effort as each sustainability tool in the literature focuses on different aspects. Therefore, it is important to analyze and compare the main sustainability assessment tools that have already been identified in chapter 2 further. Table 4.1 organizes the most important sustainability tools from chapter 2 by focus level, dimension, themes, and subthemes. Based on these information it is possible to derive dimension specific themes in the following section of this chapter.

4.3.1 Themes for Environmental Sustainability

The environmental dimension traditionally gains most of the attention in terms of sustainability, and it is the dimension discussed in most detail in the literature.

Therefore, current integrated tools use a wide range of themes to evaluate the environmental performance. With regards to Table 4.1 however, it can be identified that most tools use relatively similar themes and subthemes. Furthermore, all of them focus on the external impacts on the environmental system. Based on Table 4.1 the following main themes are derived:

a) Natural resources & assets: This theme assesses a factory's use of energy, water and material as well as the amount of waste created by the factory.

b) Pollution: This theme evaluates a factory's contribution to climate change and global warming. Additionally, it takes substances into account that present hazards to human health or the environment.

4.3.2 Themes for Social Sustainability

Recently, the public and especially stakeholders shifted the focus from environmental-related to social-related issues. Therefore, businesses pay increasingly more attention to the social dimension of sustainability, although the work on this topic is still insufficient (Labuschagne et al. 2005). It is striking that the more modern tools like EICC, 2004 and BASF Seebalance, 2012 contain significantly more social aspects then the older tools, such as DJSI or OECD-CEI.

In contrast to the environmental dimension, most of the tools considering the social dimension have an internal view instead of an external view. Since the tool developed within this thesis is aimed at assessing the social sustainability at the factory level, the focus is also internal. The following themes are derived from Table 4.1 and describe the main issues of the social dimension with regard to factories:

c) Health and Safety: This theme focuses on the security and wellbeing of all employees. It evaluates the preventative measures as well as the risk potential.

d) Labor development and work satisfaction: This theme assesses the general working conditions and the continuous development of the employees and their talents.

e) Equal opportunity and decent work: This theme evaluates the compliance of equal rights and fair employment practice standards. It contains aspects such as gender equality and equal career chances.

4.3.3 Themes for Economic Sustainability

In terms of economic sustainability the review of current integrated frameworks from chapter 2 shows that there are two different understandings of economic sustainability. Since OECD and UN-CSD are located at the global and national level, it is obvious that they take impacts from the economic system at the national and global levels into account. However, GRI assesses sustainability at a company level and considers "organization's impacts on the economic circumstances of its stakeholders and on economic systems at the local, national, and global levels" (Global Reporting Initiative 2011). All three frameworks focus on the general economic performance and development (see Table 4.1). Thus, there are two approaches that can be taken: one approach takes the external impacts on the entire economic systems into consideration, while the other focuses on the internal economic impacts of a business. The DJSI as well as the EICC consider economic performance in terms of the internal management, whereas the BASF and FPSI frameworks attempt to minimize their costs

(see Table 4.1). Consequently, it is necessary to choose between the two different approaches.

With regards to the statement that the first goal of businesses towards sustainability is to stay in business, the focus within this study is internal. Activities at the factory level contribute to the overall profitability of the company and only subsequently contribute to the economic system on a broader, national level (Labuschagne et al. 2005). Therefore the following themes are derived based on the DJSI, EICC, BASF, FPSI and Walmart-Scorecard:

f) Financials: This theme takes the internal financial stability of factories into account by assessing the profits.

g) Development: This theme focuses on the investment and expenditures on future development and Environment, Health and Safety compliance.

Table 4.1: Overview of existing frameworks and derivation of a new framework

Dimension	Themes/Sub-Theme	Global OECD-CEI	Country UNCSD-ISD	Sector EICC	Corporate GRI	Corporate DJSI	Corporate BASF	Product FPSI	Product Walmart	Factory New Tool
Environmental	**Pollution Issues**	x	x	x	x	x	x	x	x	x
	Emission, Effluent	x	x	x	x		x	x	x	x
	Climate Change	x	x			x				x
	Toxicity Potential	x					x			x
	Permits and Reporting			x		x				
	Restricted/Hazardous Substances			x				x		
	Risk Potential			x			x			
	Natural Resources & Assets	x	x	x	x	x	x	x	x	x
	Solid Wastes	x		x	x		x			x
	Water	x	x	x	x	x	x			x
	Energy	x		x	x	x	x		x	x
	Material	x		x			x	x	x	x
	Biodiversity	x	x		x	x				
	Land Use	x	x				x			
	Oceans, Seas and coasts	x	x							
	Compliance				x					
	Natural Hazards		x							
Social	**Health & Safety**		x	x	x	x	x	x	x	x
	for employees		x	x	x	x	x			x
	for customers				x		x	x		
	Working Accidents			x	x		x			x
	Machine Safeguarding			x						
	Industrial Hygiene and Toxicity Potential			x			x			x
	Physically Demanding Work			x						
	Emergency Preparedness			x						
	Mortality		x							
	Sanitation, Food and Housing		x	x						
	Labor Practices and Development		x	x	x	x	x			x
	Training/Education		x	x	x		x			x
	Satisfaction (Strikes)						x			
	Wages and Benefits			x			x			x
	Working Hours			x						
	Human Rights and decent Work			x	x		x			x
	Non-Discrimination			x	x					
	Freedom of Association			x	x					
	Child Labor Avoidance			x	x					
	Freely Chosen Employment			x	x					
	Gender Equality				x		x			x
	Integration of Handicapped People				x		x			
	Part Time Workers						x			
	Governance and Community		x		x	x	x			
	Corruption		x		x					
	Security/Crime		x				x			
	Investment					x	x			
	Public Policy				x					
	Demographics	x	x							
	Population Change	x	x							
Economic	**Management**			x			x			
	Brand Management						x			
	Risk & Crisis Management			x			x			
	Stakeholders Engagement						x			
	Performance and Development	x	x		x	x	x		x	x
	Innovation, R&D					x			x	x
	Market Presence				x					
	Indirect Economic Impacts	x			x					
	Exports/Trade	x	x				x			
	Financials						x	x		x
	Material Costs						x			
	Energy Costs						x			
	Profit Margins						x			x

4.3.4 Sustainability Performance Indicators

After defining themes for each dimension and the general criteria for indicators, it is now required to define and constraint the concept to a number of key performance indicators that meet all the criteria and can be measured, monitored, and recorded on a regular basis. A wide range of possible sustainability performance indicators can be found in the literature (see chapter 2). However, every indicator is not relevant to the industry and can be evaluated from an external perspective. Therefore, suitable key indicators have to be identified. To accomplish this, existing tools have to be compared and the most common key indicators have to be identified. Again, the main sustainability tools from chapter 2 are used for this analysis. A detailed overview of each tool can be found in the digital appendix. Additional sets of indicators found in the literature that focus on sustainable manufacturing are included as well: Krajnc and Glavic (2003), Velena et al. (2001) and Veleva and Ellenbecker (2001). Finally, the indicators are also tested and compared with sustainability reports published by different companies to ensure the data availability for the external use of the tool. To achieve this, the BMW Group Sustainable Value Report 2012, the BASF Report 2012 and the AkzoNobel Report 2012 are analyzed. These reports are published annually by the companies to report their figures and goals in terms of sustainability.

Generally, the study aims for using only quantitative indicators, as these are more objective and less biased than qualitative ones. It should also be possible to express each indicator in relative terms and not only in absolute terms, as different factories have to be compared on a meaningful level. Social indicators for example should expressed relative to the size of the workforce and environmental indicators relative to an appropriate measure of production such as produced units of product or an indication of produced weight.

The identified key sustainability indicators along with their dimensions, themes and units are summarized in Table 4.2.

Table 4.2: Key performance indicators of factory sustainability

Dimensions	Themes	Indicators	Unit
Environment	a) Natural resources & assets	1. Energy use	MWh
		2. Material use	Kg
		3. Freshwater consumption	m³
		4. Waste generation	Kg
	b) Pollution	5. Global warming potential	t
		6. Acidification potential	t
Social	c) Health & safety	7. Working accidents	-
		8. Safety training	-
		9. Hazardous materials	Kg
	d) Labor development & work satisfaction	10. Training and education	Hours
		11. Sickness frequency	Days
		12. Employee attrition rate	%
	e) Equal opportunity and decent work	13. Share of women in workforce	%
		14. Share of women in management positions	%
		15. Wages at lowest wage group	$
Economic	f) Financials	16. Net profit margin	%
		17. Return of capital employed	%
	g) Development	18. Investment in R&D	$
		19. Investment in staff development	$
		20. Expenditures on EHS compliance	$

While Table 4.2 gives an overview of all indicators, the detailed description of each key performance indicator will be presented in the following sections. It includes the

significance for factories, the goal in terms of sustainability and the calculation of the indicator as well as the references to indicate which indicator was taken from which existing framework.

Indicator 1:   Energy use – total energy consumption of non-renewable energy sources and adjusted consumption per unit of product

- *Significance*: A key goal of sustainable manufacturing is to reduce energy use and to switch to renewable energy sources, such as sun or wind. An increased use of energy increases pollution, results in global warming as well as the depletion of fossil fuels. As explained in chapter 3, factories are a key user of energy, which makes this indicator so significant for this framework.
- *Goal*: Reduce the energy consumption.
- *Calculation*:

$$I_{EN,1} = \sum_{t=1}^{T} E_t^{total} - E_t^{renewable} \quad [MWh] \tag{4.1}$$

Where E_t^{total} is the total energy consumption for a factory summed up over a period T. $E_t^{renewable}$ is the energy consumption from renewables for the same period T. To gather data a factory's utility bills can be used. Dividing the energy use by an appropriate measure of production – e.g. units of product/service – presents the energy intensity.

- *Reference*: BASF Seebalance, DJSI, EICC Indicators FH10.3 and FH10.4, GRI Indicator EN3, OECD-CEI, Veleva et al. (2001) Indicator 3 and 4, Walmart

Indicator 2:   Material use – total consumption of non-renewable materials and
adjusted consumption per unit of product

- _Significance_: The depletion of non-renewable materials such as fossil fuels, metals and minerals is becoming the limiting factor for traditional economic growth. Reducing material use at the factory-level is therefore a critical goal for achieving sustainable development.

- _Goal_: Reduce the material consumption

- _Calculation_:

$$I_{EN,2} = \sum_{t=1}^{T} \sum_{u=1}^{U} M_{u,t} * f_u \quad [Kg] \tag{4.2}$$

    Where $M_{u,t}$ is the quantity of resource u summed up over a period T; f_u represents the weighting factor of that resource based on the total estimated world reserves (see Table 4.3). Renewable materials are calculated with a weighting factor of 0 and are therefore not taken into account. Dividing the total materials used by an appropriate measure of production presents the material intensity.

- _Reference_: BASF Seebalance, EICC Indicator FB3.1, FPSI, OECD-CEI, Veleva et al. (2001) Indicator 2, Walmart

Table 4.3: Identifying weighting factors for material use (Kölsch 2011)

Resource u	Limit (years)	World Reserves (Mt)	Factor f_u
Coal	147	478 771	0.12
Crude Oil	41	164 500	0.39
Natural Gas	63	163 314	0.31
Brown Coal	241	142 000	0.17
NCI	1 000	18 000 000	0.01
Sulphur	9 091	600 000	0.01
Phosphorus	122	18 000	0.67
Iron Ore	70	71 000	0.45
Limestone	500	18 000 000	0.01
Bauxite	197	25 000	0.45
Sand	1 000	18 000 000	0.01

Indicator 3: *Freshwater consumption – total consumption and adjusted per unit of product*

- *Significance*: Water is considered to be the key problem of the 21st century. Access to fresh water should be a universal and human right, but limited resources and a growing population are increasing its economic value. Therefore, a goal of sustainable manufacturing is to reduce consumption of freshwater.

- *Goal*: Reduce the freshwater consumption.

- *Calculation*:

$$I_{EN,3} = \sum_{t=1}^{T} FW_t \quad [m^3] \tag{4.3}$$

Where FW_t is the quantity of freshwater summed up over a period T. To gather this data, a factory's water utility bills can be used. Dividing the total

amount of freshwater by an appropriate measure of production presents the

water intensity.

- *Reference*: BASF Seebalance, DJSI, EICC Indicators FH10.3 and FH10.4.6, GRI Indicator EN8, OECD-CEI, UNCSD-ISD, Veleva et al. (2001) Indicator 1

Indicator 4: Waste generation – total generation and adjusted per unit of product

- *Significance*: The United States generated 250,000 Million tons of waste in 2010 and the rate of waste generation is increasing constantly (EPA 2012). The major problems related to the high amount of waste are environmental pollution and the release of toxic substances that endanger human and ecosystem health.

  Goal: Reduce the waste generation.

- *Calculation*:

$$I_{EN,4} = \sum_{t=1}^{T} W_t \quad [Kg] \tag{4.4}$$

Where W_t is the amount of solid waste generated over a period T. Dividing the total amount of solid waste by an appropriate measure of production presents the relative waste generation per unit of product/service.

- *Reference*: BASF Seebalance, EICC Indicators FH12.4 and FH12.5, GRI Indicator EN22, OECD-CEI, Veleva et al. (2001) Indicator 5

Indicator 5: Global Warming Potential (GWP) – total and adjusted per unit of product

- *Significance*: Global warming potential is a measure of how much a particular emitted gas contributes to global warming, by comparing each gas at a relative scale with carbon dioxide. As presented in Table 4.4, carbon dioxide has been

assigned a GWP of 1. The effects of global warming, like melting glaciers and sea ice are significant and irreversible. As a main contributor to global warming (see chapter 3) factories are forced to reduce their emissions of greenhouse gases by the Kyoto Protocol and other international agreements.

- *Goal*: Reduce greenhouse gas emissions.

- *Calculation*:

$$I_{EN,5} = \sum_{t=1}^{T} \sum_{v=1}^{V} A_{u,t} * f_v \quad [t] \tag{4.5}$$

Where $A_{v,t}$ is the quantity of emission v summed up over a period T; f_v represents the equivalent factor of that emission relative to carbon dioxide (see Table 4.4). Dividing the total GWP by an appropriate measure of production presents the relative intensity.

- *Reference*: BASF Seebalance, EICC Indicator FH13, FPSI, GRI Indicators EN16 and EN18, OECD-CEI, UNCSD-ISD, Veleva et al. (2001) Indicator 6, Walmart

Indicator 6:   Acidification potential (AP) – total and adjusted per unit of product

- *Significance*: Acidification potential is a measure of how much a particular gas contributes to the acidification, by comparing each gas at a relative scale with sulfur dioxide. As presented in Table 4.4, sulfur dioxide has been assigned an AP of 1. Upon release, plants and soils can absorb acidic gases, leading to decreased biomass and poor soil quality. Additionally, surface waters and other water bodies may be acidified, resulting in poor water quality, thus, endangering ecosystem health.

- *Goal:* Reduce emissions of acid gasses.

- *Calculation*:

$$I_{EN,6} = \sum_{t=1}^{T} \sum_{v=1}^{V} A_{v,t} * f_v \quad [t] \tag{4.6}$$

Where $A_{v,t}$ is the quantity of emission v summed up over a period T; f_v represents the equivalent factor of that emission relative to carbon dioxide (see Table 4.4). Dividing the total AP by an appropriate measure of production presents the relative intensity.

- *Reference*: BASF Seebalance, EICC Indicator FH13, GRI Indicator EN20, OECD-CEI, UNCSD-ISD, Veleva et al. (2001) Indicator 7

Table 4.4: Identifying weighting factors for emissions (Kölsch 2011)

Emissions	CO_2	SO_x	NO_x	CH_4	HKW	NH_3	N_2O	HCl
GWP (CO_2-equivalent)	1			25	4750		298	
AP (SO_2-equivalent)		1	0,7			1,88		0,88

Indicator 7:   Work accidents – total and adjusted per employee

- *Significance*: The importance of work-place related accidents is higher than commonly assumed. Every year in the U.S. nearly 4 million people suffer a workplace injury and some of them never recover (U.S. Department of Labor 2012). Production areas pose an especially dangerous environment. Therefore, every factory's goal should be to be as safe as possible.

- *Goal*: Achieve zero working accidents.

- *Calculation*:

$$I_{SO,7} = \sum_{t=1}^{T} WA_t \qquad [-] \qquad\qquad (4.7)$$

Where WA_t is the number of workplace related accidents over a period T. Dividing the total amount of working accidents by the total number of employees presents the relative number of working accidents per employee.

- *Reference*: BASF Seebalance, EICC Indicator FH5.8, GRI Indicators LA7 and LA8, Veleva et al. (2001) Indicator 15

Indicator 8: *Safety trainings - by number of participants and adjusted per employee*

- *Significance*: Due to the generally high number of working accidents and the potentially dangerous environment of a production site, it is recommended to provide safety trainings for all employees.
- *Goal*: Increase the number of employees that participate in safety trainings
- *Calculation*:

$$I_{SO,8} = \sum_{t=1}^{T}\sum_{s=1}^{S} SE_{t,s} \qquad [-] \qquad\qquad (4.8)$$

Where $SE_{t,s}$ is the quantity of participants summed up over all safety trainings S and over a period T. Dividing the total number of participants by the total number of employees presents the relative number.

- *Reference*: BASF Seebalance, EICC Indicator FH11.5, GRI Indicators LA7 and LA8

Indicator 9:   Hazardous materials - total amount and adjusted per unit of product

- _Significance_: Hazardous materials are usually chemicals or mixtures of chemicals that are toxic, flammable, dangerously reactive or that cause other personal injury or illness. In order to protect worker's health and safety they should not be exposed to such materials.
- _Goal_: Reduce the amount of hazardous materials.
- _Calculation_:

$$I_{So,9} = \sum_{t=1}^{T} HW_t \qquad [kg] \qquad\qquad (4.9)$$

Where HW_t is the amount of hazardous waste generated over a period T. Dividing the total amount of hazardous waste by an appropriate measure of production presents the relative generation per unit of product. Since companies usually do not publish the use of hazardous materials, the indicator considers the generation of hazardous waste instead.

- _Reference_: BASF Seebalance, EICC Indicator FH11.2, Veleva et al. (2001) Indicator 8

Indicator 10:   Training and education - total hours and adjusted per employee

- _Significance_: Decent training and education programs provide several benefits for a factory. Employee performance increases as well as the job satisfaction and work morale. This, in turn, has positive consequences for the overall factory performance.
- _Goal_: Increase employee training.

- *Calculation*:

$$I_{So,10} = \sum_{t=1}^{T} TH_t \quad [hours] \tag{4.10}$$

Where TH_t is the quantity of training hours summed up over a period T. Dividing the total number of training hours by the total number of employees presents the relative number of training hours per employee.

- *Reference*: BASF Seebalance, EICC Indicator FL.3.10, GRI Indicator LA10, UNCSD-ISD Veleva et al. (2001) Indicator 18

Indicator 11:   Sickness frequency - total number of sick days and adjusted per employee

- *Significance*: It is widely recognized that work satisfaction can be measured through the number of sick days. A dissatisfied employee is more likely to call in sick than a satisfied one. Therefore, factories have to increase work satisfaction in order to minimize the number of working hours lost and to increase employee performance.
- *Goal*: Reduce sick days by increasing work satisfaction.
- *Calculation*:

$$I_{So,11} = \sum_{t=1}^{T} \sum_{e=1}^{E} SD_{t,e} \quad [days] \tag{4.11}$$

Where $SD_{t,e}$ is the quantity of sick days summed up over all employees E and over a period T. Dividing the total number of sick days by the total number of employees presents the relative number of sick days per employee.

- *Reference*: EICC Indicator FH6.8, Veleva et al. (2001) Indicator 19

Indicator 12: Employee attrition rate – rate of new employees and employee

turnover

- _Significance_: The employee attrition rate generally indicates how long employees tend to stay. Therefore, this is another indicator that reflects employee well-being and work satisfaction. However, this indicator may also be influenced by factors outside of a company's control e.g. strong competitors or the general economic situation. For this reason it is important to consider both, indicator 11 and indicator 12 in order to make a statement about job satisfaction.
- _Goal_: Reduce the employee attrition rate by increasing work satisfaction.
- _Calculation_:

$$I_{So,12} = \sum_{t=1}^{T} \frac{E_t^{leaving}}{\frac{E_{t=1} + E_{t=T}}{2}} * 100 \quad [\%] \tag{4.12}$$

Where $E_t^{leaving}$ is the number of employees who left summed up over a period T, divided by the average total number of employees, where $E_{t=1}$ is the number of employees at the beginning of the period and $E_{t=T}$ at the end of the period.

- _Reference_: GRI Indicator LA2, Veleva et al. (2001) Indicator 17

Indicator 13: Share of women among the total number of employees

- _Significance_: Social diversity is an integral part towards sustainability and makes a contribution to company's efficiency. Therefore, gender equality is an important topic for modern companies. It is expressed by the share of women in the total workforce.
- _Goal_: Increase the share of women to a reasonable level.

- *Calculation*:

$$I_{So,13} = \frac{F}{E} * 100 \quad [\%] \tag{4.13}$$

Where F is the total number of women divided by the total number of employees E.

- *Reference*: BASF Seebalance, EICC Indicator FL9.7, GRI Indicator LA13

Indicator 14:   Share of women in management positions

- *Significance*: The share of women in management positions is another indicator that reflects gender equality and equal opportunities.

- *Goal*: Increase the share of women to a reasonable level.

- *Calculation*:

$$I_{SO,14} = \frac{F}{MA} * 100 \quad [\%] \tag{4.14}$$

Where F is the total number of women divided by the total number of managers MA.

- *Reference*: BASF Seebalance, GRI Indicator EN20

Indicator 15:   Wage at lowest wage group per year

- *Significance*: Fair labor practices include adequate wages and benefits for all employees. Especially manufacturing sites employ a high number of workers at the lowest wage group. Therefore, it is important that the remuneration of this group is adequate in order to increase employee motivation and morale at factory level.

- *Goal*: Increase the wages to a reasonable level.

- *Calculation*:

$$I_{SO,15} = WL \quad [\$] \tag{4.15}$$

Where WL is the wage of lowest wage group per year.

- *Reference*: BASF Seebalance, EICC Indicator FL7

Indicator 16:   Net profit margin

- *Significance*: Net profit margin represents the percentage of revenue remaining after all operating expenses, interest and taxes have been deducted from a company's total revenue. This indicator represents the economic performance and indicates how successful a company is, which is critical for investors.
- *Goal*: Increase net profit margin.
- *Calculation*:

$$I_{EC,16} = \sum_{t=1}^{T} \frac{TR_t - TE_t}{TR_t} \quad [\%] \tag{4.16}$$

Where TR_t is the total quantity of revenues, minus the total quantity of expenses TE_t summed up over a period T, divided by the total revenues.

- *Reference*: BASF Seebalance, GRI Indicator EC1

Indicator 17:   Return of capital employed

- *Significance*: Another indicator that reflects the economic performance of a company is the return of capital employed. This indicator measures the profitability of a company by expressing how much it is gaining from its assets and liabilities.
- *Goal*: Increase return of capital employed.

- *Calculation*:

$$I_{EC,17} = \sum_{t=1}^{T} \frac{NOPAT_t}{CE_t} \qquad [\%] \qquad\qquad (4.17)$$

Where $NOPAT$ is the net operating profit after tax summed up over a period T, divided by the capital employed CE_t.

- *Reference*: GRI Indicator EC1

Indicator 18:   Investment in R&D - total and adjusted per employee

- *Significance*: Investment in research and development includes expenditures on test equipment, machines, and tools. The goal of these type of investments is to consistently keep the production plant in line with the most up-to-date technology, to improve productivity, and to be innovative.
- *Goal*: Increase investments in R&D.
- *Calculation*:

$$I_{EC,18} = \sum_{t}^{T} IP_t \qquad [\$\ million] \qquad\qquad (4.18)$$

Where IP_t is the amount of expenditures on R&D summed up over a period T. Dividing the total amount by the total number of employees presents the relative amount of investment in R&D.

- *Reference*: DJSI, Walmart

Indicator 19:   Investment in staff development - total and adjusted per employee

- *Significance*: Investment in staff development includes expenditures on training, workshops and continuing professional and personal development. The goal of

these type of investments is to improve business performance, to promote organizational learning and to gain long-term competitive advantages.

- *Goal*: Increase investments in staff development.

- *Calculation*:

$$I_{EC,19} = \sum_{t}^{T} ID_t \qquad [\$\, million] \qquad (4.19)$$

Where ID_t is the amount of expenditures on staff development summed up over a period T. Dividing the total amount by the total number of employees presents the relative amount of expenditures on staff development.

- *Reference*: BASF Seebalance, GRI Indicator LA10

Indicator 20:   Expenditures on EHS compliance - total and adjusted per employee

- *Significance*: Expenditures associated with Environment, Health, and Safety (EHS) compliance reduce the economic performance of the factory. The goal should be to reduce the costs though cleaner production or pollution prevention in order to increase profits.

- *Goal*: Reduce EHS compliance costs.

- *Calculation*:

$$I_{EC,20} = \sum_{t}^{T} EHS_t \qquad [\$\, million] \qquad (4.20)$$

Where EHS_t is the amount of expenditures on Environment, Health, and Safety compliance summed up over period T. Dividing the total amount by the total number of employees presents the relative amount of expenditures on EHS.

- *Reference*: GRI Indicator EN30, Veleva et al. (2001) Indicator 9

4.4   Judging of Sustainability Performance Indicators

After identifying the key indicators it is necessary to determine whether an indicator supports or harms a company's sustainability performance. This judgment of each indicator becomes important for the normalization and the aggregation in the next steps. Positive indicators are considered as sustainability contributing and should therefore be maximized. Negative indicators on the other hand should be minimized to support sustainability. The description of each indicator and especially their goals in the section above indicate already whether it is a positive or negative indicator. Thus, the results are summarized in the following table.

Table 4.5: Judging of key performance indicators

Indicators of positive sustainability		Indicators of negative sustainability	
Safety trainings	Net profit margin	Energy use	Working Accidents
Training and education	Investment in R&D	Material use	Sickness frequency
Share of women in workforce	Investment in staff development	Freshwater consumption	Employee attrition rate
Share of management positions		Waste generation	Hazardous materials
Wages at lowest wage group		GWP	Expenditures on EHS compliance
Return of capital employed		AP	

4.5 Normalizing of Sustainability Performance Indicators

The next step towards calculating a composite sustainability performance index focuses on the normalization of indicators. This step is important, because the indicators are expressed in different units and the combination of the indicators into the performance index requires common units to achieve a representative result. A number of normalization methods exist in the literature and the main procedures are presented in the following.

4.5.1 Normalization Methods

Minimum-Maximum

This method normalizes indicators with a positive impact on sustainability by the equation:

$$I^+_{N_{ijt}} = \frac{I^+_{ijt} - I^{+,Min}_{ij}}{I^{+,Max}_{ij} - I^{+,Min}_{ij}} \qquad (4.21)$$

Indicators with a negative impact on the other hand are normalized by the equation:

$$I^-_{N_{ijt}} = \frac{I^-_{ijt} - I^{-,Min}_{ij}}{I^{-,Max}_{ij} - I^{-,Min}_{ij}} \qquad (4.22)$$

Where $I^+_{i,j,t}$ and $I^-_{i,j,t}$ are the values for indicator i from the group of indicator j in year t with positive and negative impacts on sustainability, respectively, while $I^+_{N,i,j,t}$ and $I^-_{N,i,j,t}$ are the normalized positive and negative indicators, respectively. Overall, this

transformation results in a clear compatibility of different indicators, but it requires a valid database in order to be carried out. (Zhou et al. 2012; OECD 2008)

Distance to a reference

This method calculates the ratio between the indicator and an external benchmark. The normalized indicators are described in the following equation:

$$I_{N_{ij}} = \frac{I_{ij}}{I_{ij}^{Benchmark}}$$

(4.23)

Where $I_{i,j}^{Benchmark}$ is benchmark for indicator i from the group of indicators j. In this case, it is possible that the normalized value is higher than 1, which indicates that the performance of the factory is better than benchmark. (Zhou et al. 2012; OECD 2008)

Percentage over annual differences

Finally, the method "Percentage over annual differences" is the third main normalization approach discussed in this chapter. It focuses on the development of the indicators over time. Therefore, each indicator is transformed using the following formula:

$$I_{N_{ijt}} = \frac{I_{ijt} - I_{ij,t-1}}{I_{ij,t-1}} * 100$$

(4.24)

The normalized indicator is dimensionless. Nevertheless, the disadvantage of this method concerns the case $t = t^o$. In that case, the indicators cannot be normalized by the given equation and the data would be lost during the analysis. (Zhou et al. 2012)

4.5.2 Evaluation of Normalizing Method for Factory Sustainability

After reviewing the main normalizing methods, it is necessary to evaluate which method fits best. This evaluation is not as straightforward as evaluating the weight of the model. All of the described methods require a database or a set of reference data in order to transform the indicators. However, since there is no database available for the indicators, normalization is not possible for one data set of indicators. Nevertheless, the tool created within this thesis does not only attempt to assess a single factory, but also to compare different factories with each other and to evaluate the development over time. These three different cases lead to the following conclusion:

- Assessing a single factory → No normalization possible

- Comparing different factories → "Distance to a reference"

- Development of a factory → "Percentage over annual differences"

4.5.3 Implementation within the Framework

As mentioned above, the selection of the normalizing method depends on the purpose of use. Regarding the comparison of factories the best method to use is the "distance to a reference". However, some aspects of this method have to be slightly modified in order to meet the requirements within this thesis. As there is no large database available, there is also no external benchmark value available. Although, it is not possible to normalize one factory with a reference value, it is still possible to compare two or more factories, by assigning the value 1 to the inferior factory for each indicator and therefore making it a reference factory. The remaining factories are evaluated relatively to that factory with a value between 0 and 1. The closer the value is to 0, the better the performance of the factory according to that indicator.

The second case, where it is necessary to normalize the indicators, regards the development of a factory over time. Here, the method "Percentage over annual differences" provides the best comparison. In contrast to the other method, this method can be implemented as described in the previous section, without modifying any aspects. Nevertheless, if only few data sets are available it is recommended to use the same normalization method as explained above, because the data for $t = t^o$ would be lost during the analysis.

4.6 Weighting of Sustainability Performance Indicators

The next step towards developing a sustainability assessment framework focuses on weighting the indicators. Not only is it important to weight the indicators against each other, but also with regard to the different industries (see chapter 2), and their impact on factory performance. The main reason for weighting indicators is to determine the individual importance of these indicators towards an overall goal. Although, this purpose is understood intuitively, it remains difficult to determine weights with sufficient accuracy (Krajnc, Glavič 2005). "The relative importance of the indicators is a source of contention" (OECD 2008, p33). Therefore, a number of different weighting techniques exist in the literature. Some are derived from statistical methods such as the Data Envelopment Analysis and others from participatory methods like the Analytic Hierarchy Process. Additionally, there is also a method that avoids the relative importance of the indicators and weights them equally. In the next section, the theory behind those weighting techniques is discussed and how they meet the criteria for weighting factory assessment indicators.

4.6.1 Weighting Methods

Budget Allocation Process (BAP)

This weighting procedure determines the indicator weights based on expert opinion. In general, the BAP has four different phases: first, experts in the field have to be selected for the assessment. It is essential that the experts represent a wide spectrum of knowledge and experience. Second, the selected experts have to allocate a "budget" of one hundred points to the indicator set, based on their personal judgment of the relative importance. In a third step weights are calculated as average budgets. As an optional fourth step the procedure could be iterated until convergence is reached. (Hermans et al. 2008; OECD 2008)

The main advantages of BAP are its transparent and simple application as well as its short duration. On the other hand, it also contains several disadvantages: the weights are fairly subjective and could reflect specific conditions that are not transferable from one factory to another. (Zhou et al. 2012)

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process is another participatory method similar to the Budget Allocation Process. However, this method is far more complex and consists of a mathematical approach. The AHP was developed by Saaty in the early 1970s and is a widely accepted technique for multi-attribute decision making. Singh et al. used this method to develop a composite sustainability performance index for the steel industry (Singh et al. 2007), Krajnc et al. applied it to a case study on the sustainability performance of the oil and gas industry (Krajnc, Glavič 2005) and Hermans et al. implemented it to a limited extend in the road safety research (Hermans et al. 2008).

As a first step of this method it is necessary to translate a complex problem into a hierarchy. The top element of the hierarchy is the overall goal of the decision model and the criteria and indicators contributing to the decision are represented at the lower levels. The second step requires a pair-wise comparison between each pair of indicators. Experts have to judge "how important is indicator j relative to indicator i ?". Values on a scale from 1 to 9 are assigned to show the intensity of preference. The larger the number, the greater the importance. (Saaty 1980) In the next step the results are presented in a matrix to obtain the relative weights of each indicator. For a matrix Q x Q, only Q-1 comparisons are necessary to find weights for Q indicators (OECD 2008). Finally, it is required to find the eigenvector with the largest eigenvalue from the matrix. The eigenvector presents the weights and the eigenvalue measures the consistency of each judgment. Inconsistency within this method can always occur, because it is based on people's beliefs and it is human nature that they may be inconsistent. However, a consistency ratio of 0 indicates a perfectly consistent matrix, while a ratio equal to 1 indicates meaningless or random judgments. A suggested rule-of-thumb says that a ratio of less than 0.1 does not drastically affect the consistency of the weights. (Saaty 1980; Singh et al. 2007)

Aside from the problem of possible inconsistency, the subjectivity of judgment is another negative characteristic of the method. Each expert judges the indicators based on his or her own knowledge and experiences. With that, the possible inconsistency is also related to subjectivity (Hermans et al. 2008). Despite these disadvantages, AHP is a comprehensive and popular technique and the information from well-selected experts is valuable for weighting indicators. In contrast to most other methods AHP allows both, quantitative and qualitative criteria to be entered into the model and it assesses different levels of criteria.

Data Envelopment Analysis (DEA)

The Data Envelopment Analysis, developed by Charnes, Cooper and Rhodes (CCR) in 1978, is a linear programming method that can be used for calculating the relative efficiency of decision-making-units (DUM). In the context of this study each factory can be considered as a DUM. So the efficiency of each factory k_o is defined as the ratio of the weighted sum of outputs, y_j, to the weighted sum of inputs, x_i, in the following famous CCR model:

$$\max h_o = \frac{\sum_{j=1}^{n} w_j y_{j\,k_o}}{\sum_{i=1}^{m} v_i x_{i\,k_o}}, \tag{4.25}$$

$$\frac{\sum_{j=1}^{n} w_j y_{j\,k}}{\sum_{i=1}^{m} v_i x_{i\,k}} \leq 1, \quad k = 1, \dots, K, \qquad w, v \geq 0 \tag{4.26}$$

Here the constraints require that the unknown weights (w's and v's) are assigned to maximize the efficiency of each factory (El-Mahgary, Lahdelma 1995). To solve the original CCR model for constructing composite indicators it has to be converted to a linear form by neglecting the inputs and referring to each indicator as an output. A general DEA model for constructing such indexes has been developed by Cherchye et al. (Cherchye et al. 2007), where every factory k_o is described by the following linear programming problem:

$$CI_k = max_{w_j} \sum_{j=1}^{n} y_{jk}\, w_j \tag{4.27}$$

$$s.t. \sum_{j=1}^{n} y_{jl}\, w_j \leq 1, \quad w_j \geq 0 \tag{4.28}$$

In this case, if $y_{jk} > y_{jl}$ then the factory k performs better then factory l. The model results in a set of indicator weights w_j that maximizes the indicator value CI_k for each factory. Therefore, the weights may be different for factory k than for factory l. The weights are only restricted to be non-negative as stated by the second constraint of the model.

The DEA is different compared to the other weighting methods. The model results in factory-specific weights instead of one set of weights for all factories. This is a disadvantage, because factories can only be ranked and compared, if they are based on the same set of weights. Furthermore, in this approach the weights do not sum up to 1, which makes the comparison with other weighting methods difficult. Nevertheless, this method has already been used for a number of indices such as the Technology Achievement Index (Cherchye et al. 2007). The strength of the method lies in the fact that the optimal weights are directly derived from the data and that no normalization is needed.

Another approach to implement the DEA is proposed by Hermans et al. In order to develop a road safety performance index the authors combine the DEA model with the BAP model. In that case the weights are bounded by the BAP and the authors were able to develop one model for all DUMs. The DEA assesses then the efficiency. (Hermans et al. 2008) Yang and Kuo on the other hand combine AHP for weighting and DEA for measuring the efficiency (Yang, Kuo 2003).

Benefit-of-the-doubt (BOD)

The benefit-of-the-doubt presents another application of the DEA in the field of composite indicators. In contrast to the original DEA model, BOD evaluates the relative performance of the factories and not the efficiency (Cherchye et al. 2004). However, it

is based on the same model and follows the same process. The composite index CI in this case is calculated as the ratio between the actual performance of the factory and the external benchmark:

$$CI = \frac{\sum_j I_{S_j} * w_j}{\sum_j I_{S_j}^{Benchmark} * w_j} \tag{4.29}$$

Where I_{S_j} is the sub-index for the group of indicators j, while $I_{S_j}^{Benchmark}$ is their benchmarks and w_j the corresponding weight (Zhou et al. 2012). Whereas, the sub-indicator I_{S_j} is calculated by:

$$I_{S_j} = \sum_{i=1}^{m} I_{N_{ij}} * w_{ij} \tag{4.30}$$

$$s.t. \quad \sum_{i=1}^{m} w_{ij} = 1, \quad w_{ij} \geq 0 \tag{4.31}$$

Where $w_{i,j}$ is the corresponding weight of each indicator i within the group of indicator j and reflects the individual importance of each indicator during the sustainability assessment of the factory to maximize the value for CI. The specific weights can be determined by solving the same linear programming problem from the original DEA model (see equation 4.25).

Since BOD can be seen as a specialized version of the original DEA model, the DEA's advantages and disadvantages also apply for this method. However, this method has already been used for a number of indeces. It was originally proposed in the context of a macroeconomic performance assessment by Melyn and Moesen in 1991 and later adapted by Cherye and Kuosmann for a cross-country assessment of human development and sustainable development performance (Cherchye et al. 2004).

Equal Weighting (EW)

As its name already indicates, the same weight is assigned to each indicator. This implies that all indicators have the same importance and that no statistical or participatory approach is used to determine the weights. The value of the weights is simply calculated by $\frac{1}{l}$ where l is the number of all indicators and 1 represents the sum of all weights (Zhou et al. 2012; Hermans et al. 2008).

Although this method appears too simple from a scientific point of view, several composite indicators like the Environmental Sustainability Index or the European Innovation Scoreboard are constructed by equal weighting (Hermans et al. 2008). The main disadvantage is the fact that is does not offer any insights on indicator importance and it does not reflect reality. However, this method can be considered as a solution in case no other weighting method presents valid results.

4.6.2   Evaluation of Weighting Method for Factory Sustainability

In order to analyze which weighting method is best fitted and suitable for a framework to assess factory sustainability it is required to develop specific criteria that has to be fulfilled.

- *Quantitative and qualitative data*: Since the set of indicators that are used for this framework may be extended by quantitative indicators it is necessary that the weighting method can handle both types of data.
- *Objectivity*: Indicators should be weighted without bias in order to be meaningful and to decrease personal preferences.
- *Insights into indicator importance*: The overall goal of the tool developed within this study is to assess the sustainability performance of factories. Therefore,

it is important that indicators reflect their individual importance towards factory sustainability.

- *Transferability*: The developed tool is supposed to allow the user to compare factories with each other. In order to do so, it is required that the indicator specific weights are always valid and transferable from factory to factory.

- *No need for a database*: Due to the fact that there is no large accessible database for each indicator, the weighting has to be possible without including a lot of data.

In order to identify a weighting method the methods introduced previously are presented in a structured way in Table 4.6, where each method is assessed towards the fulfillment of the before derived criteria:

Table 4.6: Evaluation of weighting methods

Method	Quantitative/ qualitative data	Objectivity	Insights in indicator importance	Transferability	No need for a database
BAP	+	-	O	O	+
AHP	+	O	+	+	+
DEA	O	+	O	-	-
BOD	+	+	O	-	-
EW	+	-	-	+	+

+ = Criteria fulfilled   O = Fulfilled with restriction   - = Criteria not fulfilled

A method fulfilling all the criteria cannot be identified. However, of all the reviewed weighting methods, the AHP gives the best results. It is therefore used to weight the different indicators in the next section of this chapter.

4.6.3 Implementation within the Framework

The first step towards implementing the AHP requires the formulation of an AHP model, which synthesizes the composite sustainability performance index into a systematic hierarchal structure. The overall goal of the problem, to develop a composite sustainability performance index, is represented at the top level of the hierarchy as shown in Figure 4.3. The three dimensions of sustainability, which are identified to achieve the goal form the second level. The third level consists of the various key performance indicators, which are grouped with respect to the three dimensions and shall be weighted specifically to the industry that is being evaluated.

Indicator are weighted industry specific
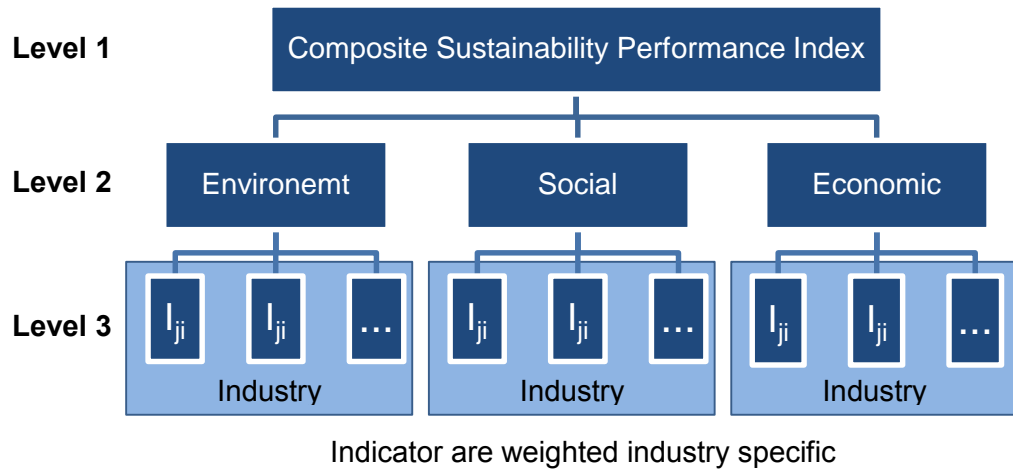
Figure 4.3: AHP model for a composite performance index

In the next step, all three levels have to be assessed using the AHP approach of pair-wise comparisons according to their impact on the next level. A group of four sustainability experts is asked to judge the indicators by estimating a preference factor of each indicator relative to another. The preference factors follow a scale from 1 to 9, where 1 indicates equality between the two indicators and 6 for example means that one indicator is six times more relevant than the other. However, the evaluation has to be carried out in an industry specific manner for each one of the six main industries

68

that have been identified in chapter 3. For this reason, the assessment team that is asked to carry out the evaluation is composed of experts from different sustainability leading companies, like BMW, Cisco, and AkzoNobel, for example. This ensures that the evaluation is practically oriented and comprehensive. The exact questionnaire that was distributed to the experts is shown in the appendix A1.

The process of pair-wise comparisons and relative weight evaluation is presented in the following based on an example considering the environmental dimension within the basic materials/resources industry. The pair-wise comparison matrix for this example is shown below.

Table 4.7: Pair-wise comparison matrix for evaluation of estimated weights of environmental indicators

	Energy	Material	Water	Waste	GWP	AP
Energy use	1,00	2,00	3,00	3,00	1,00	2,00
Material use	0,50	1,00	3,00	1,00	0,50	1,00
Freshwater use	0,33	0,33	1,00	2,00	0,50	1,00
Waste	0,33	1,00	0,50	1,00	0,50	2,00
GWP	1,00	2,00	2,00	2,00	1,00	2,00
AP	0,50	1,00	1,00	0,50	0,50	1,00

The first column of the matrix includes the indicators and is provided to the expert. The second column is filled in by judging indicator 2, 3,..n with respect to indicator 1. Then the process of comparison is repeated for all other columns of the matrix.

The next step requires a normalization of the weights. Therefore each column of the matrix in Table 4.7 is normalized by dividing each indicator weight by the sum of all relative weights in the column and then averaging them. The results are presented in Table 4.8.

Table 4.8: Normalized values of environmental indicators

	Energy	Material	Water	Waste	GWP	AP	Average weight
Energy use	0,27	0,27	0,29	0,32	0,25	0,22	0,27
Material use	0,14	0,14	0,29	0,11	0,13	0,11	0,15
Freshwater use	0,09	0,05	0,10	0,21	0,13	0,11	0,11
Waste	0,09	0,14	0,05	0,11	0,13	0,22	0,12
GWP	0,27	0,27	0,19	0,21	0,25	0,22	0,24
AP	0,14	0,14	0,10	0,05	0,13	0,11	0,11

After calculating the weights, it is required to check the consistency of the judgment. Inconsistency is likely to occur when the expert exaggerates or makes errors during the pair-wise comparison. For example, if material use is preferred over energy use and material use is not as important compared to waste, consequently waste should be more preferred over energy use. In case this logical chain is not followed, inconsistencies will occur. As stated above, the consistency index ranging from 0-1 can be applied in this scenario to test for discrepancies in the evaluation and weighting of the indicators. To check for consistency it is necessary to find a vector by multiplying the pair-wise comparison matrix with the weight vector.

$$
\begin{pmatrix}
1.0 & 2.0 & 3.0 & 3.0 & 1.0 & 1.0 \\
0.5 & 1.0 & 3.0 & 1.0 & 0.5 & 1.0 \\
0.33 & 0.33 & 1.0 & 2.0 & 0.5 & 1.0 \\
0.33 & 1.0 & 0.5 & 1.0 & 0.5 & 2.0 \\
1.0 & 2.0 & 2.0 & 1.0 & 1.0 & 2.0 \\
0.5 & 1.0 & 1.0 & 0.5 & 0.5 & 1.0
\end{pmatrix}
*
\begin{pmatrix}
0,27 \\
0,15 \\
0,11 \\
0,12 \\
0,24 \\
0,11
\end{pmatrix}
=
\begin{pmatrix}
1,73 \\
0,97 \\
0,72 \\
0,75 \\
1,49 \\
0,69
\end{pmatrix}
\tag{4.32}
$$

In the next step the resulting vector has to be divided by the weights vector.

$$
\begin{pmatrix} 1.73\ /0{,}27 \\ 0.97\ /0.15 \\ 0.72\ /0.11 \\ 0.75\ /0.12 \\ 1.49\ /0.24 \\ 0.69\ /0.11 \end{pmatrix} = \begin{pmatrix} 6.40 \\ 6.49 \\ 6.40 \\ 6.23 \\ 6.32 \\ 6.27 \end{pmatrix}
\tag{4.33}
$$

Then, the consistency index has to be calculated by inserting the overall average of the final vector is $\lambda_{max} = 6.35$ into the following formula:

$$
CI = \frac{\lambda_{max} - n}{n - 1} = \frac{6.35 - 6}{6 - 1} = 0.07
\tag{4.34}
$$

Finally, the consistency ratio can be calculated using the following formula:

$$
CR = \frac{CI}{RI} = \frac{0.07}{1.24} = 0.056
\tag{4.35}
$$

Where CI is divided by a random matrix consistency index, RI, providing a normalized value (Deturck 1987). With regard to the CR value of 0.056, it can be concluded that the judgment is consistent. The consistency ratio has to be calculated for each judgment and also for the overall weights combining each judgment. However, the procedure is always similar to the example shown above.

The results of the entire assessment procedure for each industry are summarized in the appendix A2.

4.7   Calculating the Sub-Indices

After weighting and normalizing each indicator, the next step requires to group these basic indicators into the sustainability sub-index for each group of sustainability indicators. In the context of this thesis there are three groups of indicators;

environmental, economic, and social and therefore also three sub-indices, respectively. Sub-indices can be derived as shown in the following equation:

$$I_{S_j} = \sum_{ji}^{n} w_{jt} * I_{N_{ji}}$$ (4.36)

$$s.t. \quad \sum_{ji}^{n} w_{ji} = 1, \quad w_{ji} \geq 0$$ (4.37)

Where SI_j is the sustainability sub-index for each group of indicators j. Since the framework uses the AHP weighting method, the first constraint restricts the sum of all weights w_{ji} of indicator i for the group of sustainability indicators j to be equal to 1.

4.8 Combining the Sub-Indices into the Composite Index

As a final step it is required to combine all three sub-indices into one overall composite sustainable performance index. This index can be calculated as shown in the following equation:

$$CI = \sum_{j=1}^{n} w_j * I_{S_j}$$ (4.38)

$$s.t. \quad \sum_{j=1}^{n} w_j = 1, \quad w_j \geq 0$$ (4.39)

Where CI is the overall sustainability composite index for the factory that has been assessed.

4.9   Final Framework of the Factory Sustainability Assessment Tool

Reviewing the concept of the framework that is used to assess factory sustainability in this thesis shows that three different cases can be evaluated using this assessment tool.
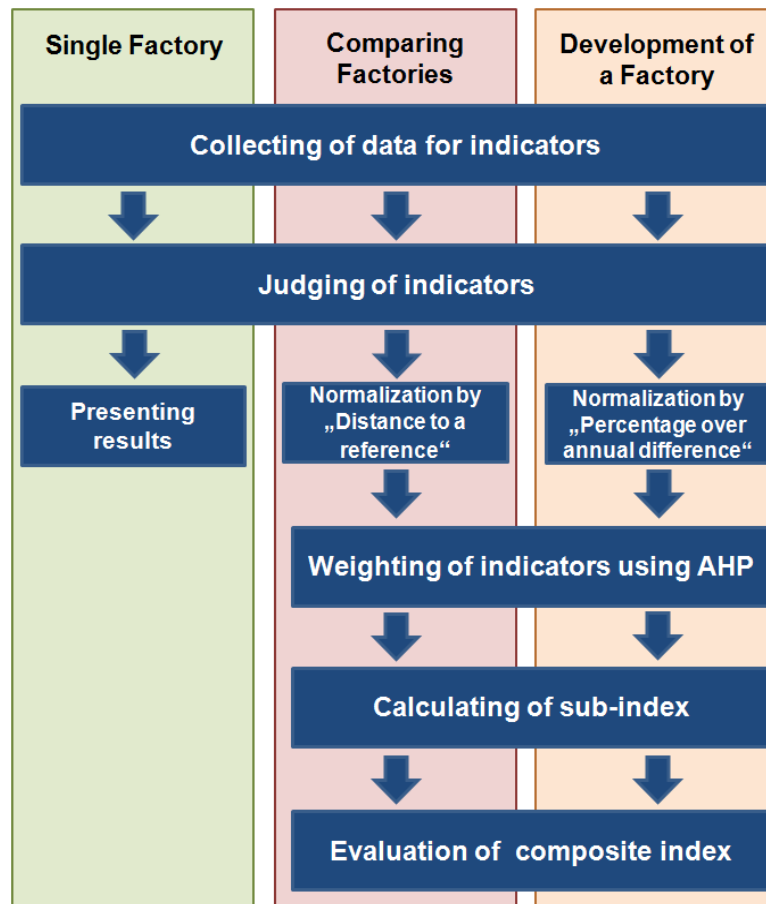
Figure 4.4: Scheme of the final framework

First, it is possible to consider only a single factory. The collected data for this case can be judged according to the results of section 4.4, but since there is no reference data available for each indicator, normalization cannot be performed. This process ends here with the presentation of the results. The other case regards the comparison of two or more factories. After collecting the relevant data for each indicator, they can

be normalized by using the method "distance to a reference", where the value 1 is assigned to the worst factory for each indicator. In a next step it is possible to weight the data according to their importance towards an overall goal. Afterwards the normalized and weighted indicators can be combined to a sub-index and then to an overall composite index. The third case considers the development of a factory over time. This case is similar to the case "comparison of factories". The only difference is that the normalization step uses the method "percentage over annual differences". This is the best suited method, because only one factory is considered over time.

CHAPTER 5 – IMPLEMENTATION OF THE TOOL

After developing the framework of the tool in the previous chapter, it is now required to convert it into a computer-based tool. For a user friendly digital assessment and data processing it is decided to implement the tool in MS Excel by using VBA. Therefore, the first section of the chapter presents the programming environment Visual Basic for Application and its characteristics, in order to show that it satisfies all needs. In the second section, the implementation and structure of the tool will be presented in more detail.

5.1　Characteristics of Visual Basic for Application

Visual Basic for Applications (VBA) is the programming environment for Microsoft Office and its associate applications. It allows object-oriented programming by using a modern language that resembles most of the popular programming languages such as Pascal or C. VBA is used for the same reasons macros are used, but it offers a finer degree of control and more possibilities than macros alone (Microsoft 2013). Moreover, it was decided to implement the tool in VBA because of the following characteristics:

- **Stepwise processing:** The input and processing of the data is complex and should be performed in several steps. VBA simplifies the coordination and the process.

  For example: Each dimension has its own input mask.

- **Error prevention:** The data has to be entered in a specific way and the tool should prevent the user from making mistakes. VBA can ensure to accept only a certain format.

  For example: The input mask cannot be closed before the user has entered all data.

- **Error messages:** When the user makes an error, the error and the possible remedy should be displayed with individual information and instructions for the user. This ensures a minimal rate of errors.

  For example: A message box will be displayed to show the user which information is missing in order to match the input mask.

- **Automatic analyses:** The tool calculates sub-indices and a composite sustainability index. Moreover, the results should be presented graphically based on different charts. This requires an iterative calculation process, as well as a process to create and format the charts. These tasks can be automated by using VBA to write explicit instructions for Excel.

  For example: Any company from the database can be evaluated at the touch of a button.

These characteristics indicate that by implementing the tool in VBA, it can easily be used on any computer with an MS Excel installation without the need of sophisticated programming experience. Furthermore, MS Excel is usually available at any company.
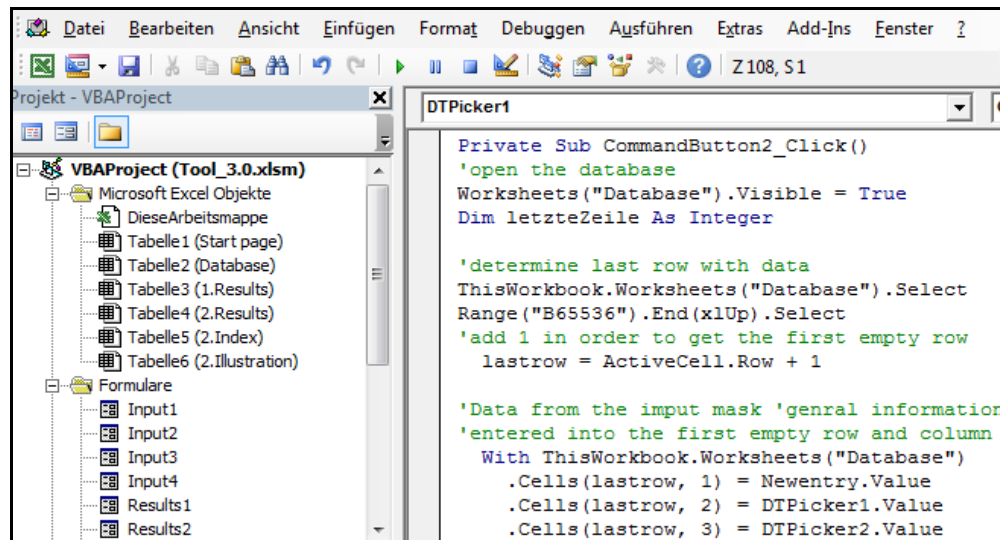
5.2   Implementation of the Tool

The start page of the tool is shown in the figure below. It is simply structured with clear symbols and colors. It is divided into the left side with buttons for data entry and the right side with higher level functions and buttons for the data processing. These buttons and functions are described in more detail in the next sections of this chapter.
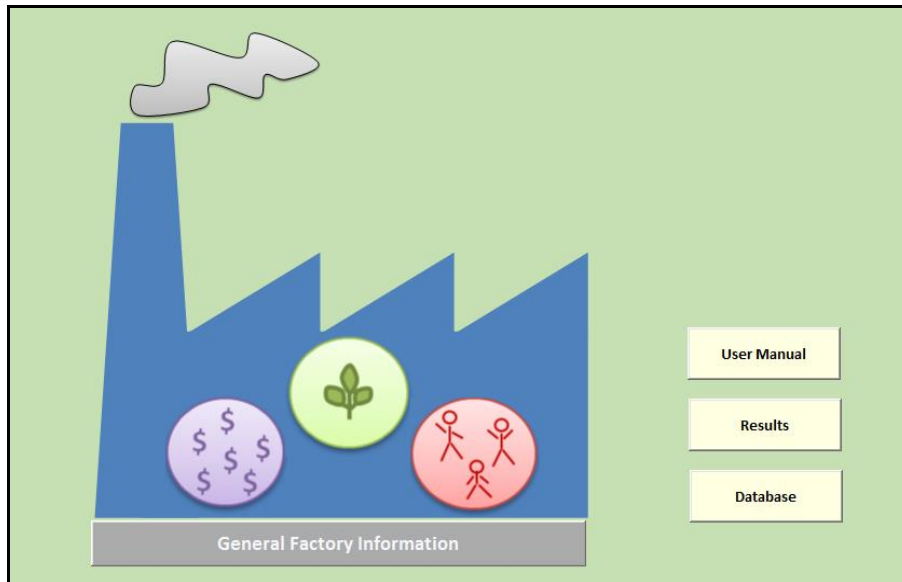
Figure 5.1: Start page of the tool

While Figure 5.1 shows the user view of the tool in Excel, Figure 5.2 presents the VBA structure behind the tool. It indicates that the tool consists of 6 tables and 29 user forms. With VBA it is possible to write a program code for each object (buttons, user forms etc.). By selecting the object it is possible to get access to the code and to edit it on the right side of the VBA window (see Figure 5.2).

Figure 5.2: VBA structure of the tool

77

5.2.1 Implementation of the Data Input

The data input is divided into four different steps. As mentioned above, the start page of the tool in Figure 5.1 shows all four buttons for the input at the left side. One for the general factory information and one for each dimension.

The input mask for the general information is presented in Figure 5.3. Besides the start and end date of the evaluation period, the user has to insert general information about the company (name, size of workforce and number of produced units). Additionally, it is asked in which sector and industry the company is operating. Here the user can choose between the sectors identified in chapter 3. This decision influences the weighting in the next steps.

Figure 5.3: General factory information input mask

After entering all information, the user has to confirm the input and close the mask by pushing the button "OK" and all information are automatically stored in a general database. The following figure presents the program code for this process.

```
Private Sub CommandButton2_Click()
'open the database
Worksheets("Database").Visible = True
Dim letzteZeile As Integer

'determine last row with data
ThisWorkbook.Worksheets("Database").Select
Range("B65536").End(xlUp).Select
'add 1 in order to get the first empty row
  lastrow = ActiveCell.Row + 1

'Data from the imput mask 'genral information' are always
'entered into the first empty row and column A to H
  With ThisWorkbook.Worksheets("Database")
    .Cells(lastrow, 1) = Newentry.Value
    .Cells(lastrow, 2) = DTPicker1.Value
    .Cells(lastrow, 3) = DTPicker2.Value
    .Cells(lastrow, 4) = Company.Value
    .Cells(lastrow, 5) = Industry.Value
    .Cells(lastrow, 6) = Industry2.Value
    .Cells(lastrow, 7) = Employee.Value
    .Cells(lastrow, 8) = Product.Value

  UserForm1.Hide
  Unload UserForm1

End With
End Sub
```

Figure 5.4: VBA code to store information in database

In a next step the user has to enter data into the input mask for the environmental

dimension (see Figure 5.5). Starting with the first indicator to the last one. This mask is

similar to the input mask described above. After confirming the input, a code

comparable to the code in Figure 5.4 will store the information in the database at the

correct position.

79

Figure 5.5: Environmental dimension input mask

Additionally, the user has to complete the data entry for the social and economic dimensions accordingly.

Generally, the tool provides assistance to avoid entry errors. Some entry fields allow only integers or strings to prevent errors during calculation. Moreover, it is not possible to close the input mask before the user entered all information.

5.2.2 Implementation of the Data Processing

Besides the aspect of data entry, the tool considers also the aspect of data analysis and evaluation. By pushing the button "Results" on the start page another user form opens and the user can select one out of three different cases:

Case 1: Assessing one factory

The first case assesses only a single factory. The user form provides checkboxes to select a factory from the database. The selection is made based on the name of the company and also on the date of the evaluation period. Since the same company might be listed more than once, it is necessary to search the database for two variables in

order to make a clear identification. The following program code shows the iterative for-

loop, used to combine both variables.

```
Private Sub Company_Change()
Dim i As Integer
Dim rowmax As Integer

'Definition of the search area
ThisWorkbook.Worksheets("Database").Select
rowmax = ActiveSheet.Cells(65536, 4).End(xlUp).Row

'If the code finds the company in column D,
'it adds the date from column B to the array for "Date"
Date.Clear
For i = 1 To rowmax
    If Cells(i, 4) = Company.Value Then
        ComboBox1.AddItem Cells(i, 2).Value
    End If
    Next i

End Sub
```

Figure 5.6: VBA code to combine two variables

After selecting the desired company, the respective values have to be analyzed

and presented. In order to transfer the correct data it is required to search the database

for both variables, company name and date. The code in Figure 5.7 presents the code

for this process. At first the two search variables company name and date are declared

(search, searchc). Next, the database is searched iteratively with a do-while loop for

an entry with the correct company name in one column and with the correct date in the

next column (offset) which matches the second search variable. If an entry is found the

respective database entry is returned otherwise a massage box with an error is

displayed.

```
Dim firstaddress As String
Dim search As String, searchc As String
Dim foundc As Range
Dim bfound As Boolean
Dim row As Integer

'Definition to search for date and company
With ThisWorkbook.Worksheets("Database").Select
    search = Date1.Value
    searchc = Company.Value

'Definition where and what to find
Set foundc = Columns(4).Find(What:=searchc, After:=Cells(Rows.Count, 4))

'First the code looks for the company and compares the results with the date
'if the both variables are true it saves the row and if not the code runs again
  If Not foundc Is Nothing Then
        firstaddress = foundc.Address
            Do
              If foundc.Offset(, -2) = search Then
                  row = foundc.row
                   bfound = True
                    Exit Do
                  End If
'If the code does not find a match, it displays a messagebox
    Set foundc = Columns(4).FindNext(foundc)
            Loop While foundc.Address <> firstaddress
          If bfound = False Then MsgBox "Please check your selection for Date"
      Else
         MsgBox "Please check your selection for Comapny"
         Exit Sub
      End If
 End With
```
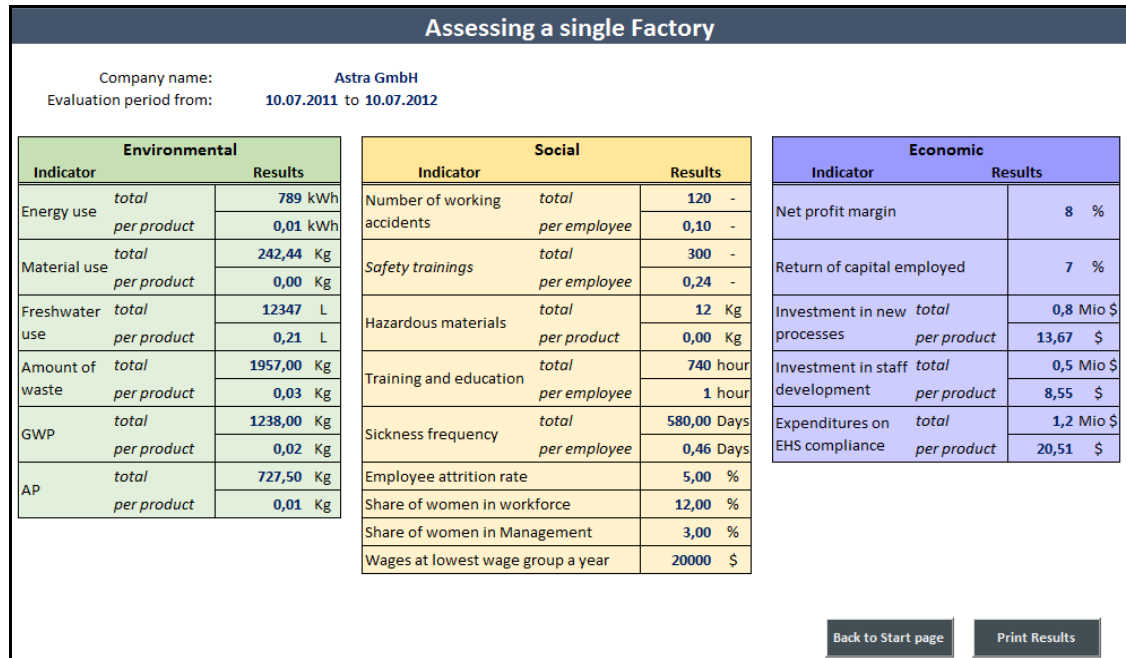
Figure 5.7: VBA code to search for two variables

Finally, the results will be presented in a structured and clear overview, as shown

in Figure 5.8. The button "Print Results" will automatically format the page and print it

out on the standard printer.

Figure 5.8: Presentation of assessment results

Case 2: Comparing different factories

In this case the user has the possibility to assess two or more factories at the same time and to evaluate them as alternatives against each other. As in case 1, the user can select the companies from the database by entering the name and the date. Therefore, this case uses similar codes as shown in Figure 5.6 and Figure 5.7. The data processing for this case is performed automatically by the tool and can be divided into three steps:

a) *Creating a structured overview*: This type of overview is shown in Figure 5.8 and will be created for each factory that is being assessed. It includes all absolute indicators and calculates for adjusted indicators per employee or per unit of production.

b) *Normalizing and comparing the indicators*: This step results in a spider chart for each dimension to visualize the results. Figure 5.9 presents an example for the environmental dimension. It shows the distribution of the assessment results and enables the identification of strengths and weaknesses of the alternative factories compared to each other.

Company	Energy	Material	Water	Waste	GWP	AP
MIN/MAX	0,02	0,01	0,25	0,07	0,05	0,03
Bruss	1,00	0,99	0,97	0,53	0,49	0,47
Acadia	0,82	1,00	1,00	1,00	1,00	1,00
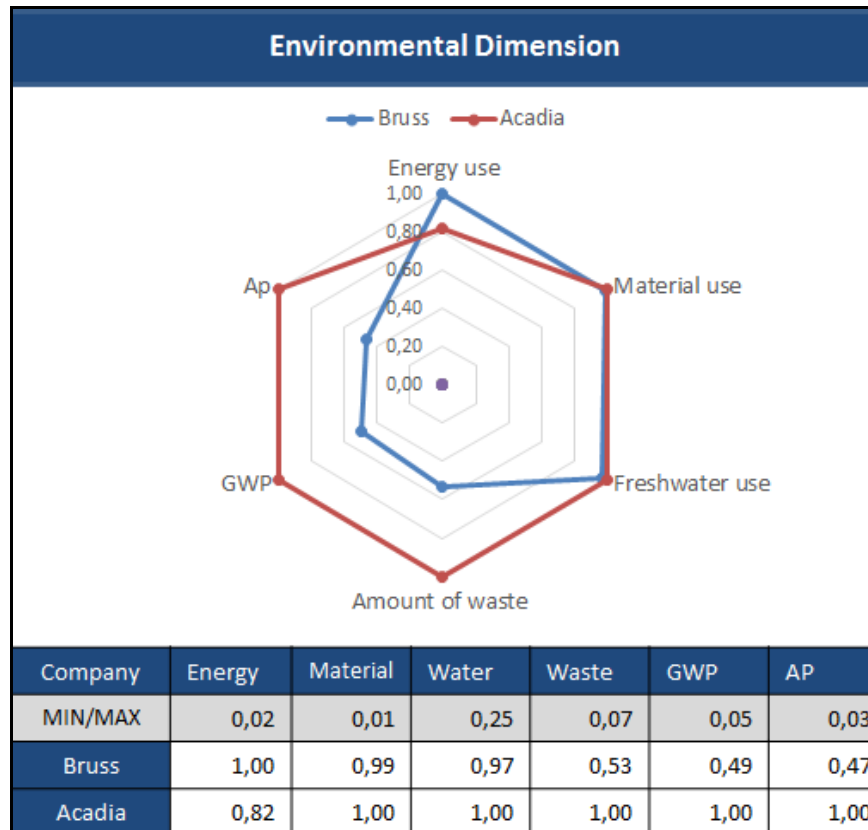
Figure 5.9: Presentation of assessment results by indicators

c) *Calculating sub-indices and an overall index:* The last step calculates an index for each dimension by weighting and aggregation of the results as described in the previous chapter. The figure below shows how the tool visualizes the results in terms of the three dimensions.
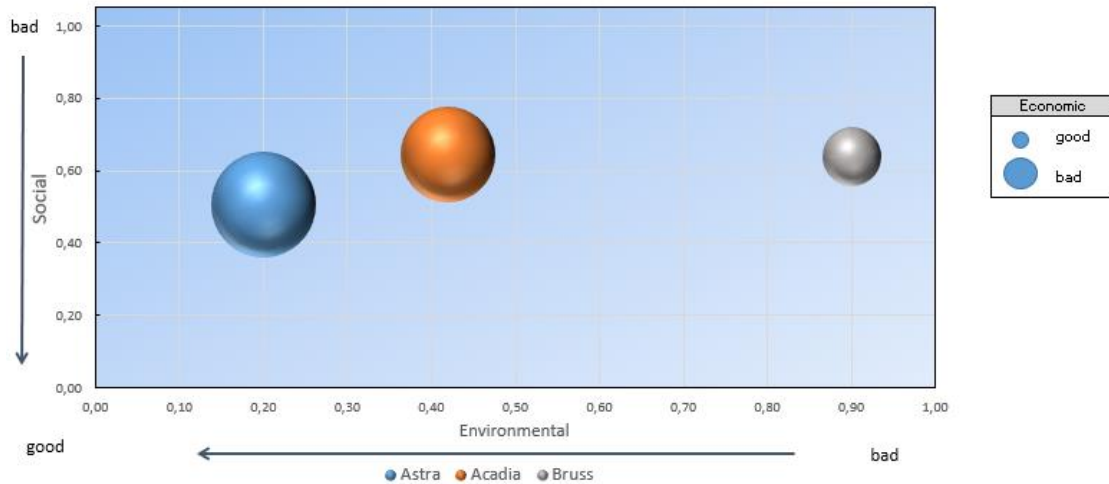
Figure 5.10:   Presentation of assessment results by dimensions

Finally, it combines the results to one overall index. Based on these numbers the user is able to determine which factory has the best sustainability performance in comparison to the other factories.

Case 3: Assessing a factory over time

The third case concerns the assessment of one factory over a period of time. The user can select different evaluation periods for the same factory and analyses the results. Generally, the data entry as well as the data processing is very similar to the second case. Therefore it is not presented any further.

CHAPTER 6 - CASE STUDY: AUTOMOTIVE INDUSTRY

After implementing the framework into a computer based tool, it has been applied to a practical case study in order to demonstrate its application and effectiveness. The case study is divided into two parts. The first part focuses on the comparison of different factories (Case 2), by analyzing the BMW plant in Dingolfing, Germany and the Daimler plant in Sindelfingen, Germany. The second part of this chapter considers the assessment of a factory over time (Case 3). In this case the results of BMW are compared for the year 2010, 2011 and 2012. However, the assessment of a single factory (Case 1) is not considered in this chapter, because it is already included when Case 2 and/or Case 3 are performed. The entire case study is carried out by using the developed sustainability assessment tool and data based on public records.

6.1 Comparison of different Factories

In this section of the case study the sustainability performance of two different factories from the automotive industry are compared with each other. One factory that is being assessed is the BMW plant in Dingolfing. This plant belongs to the BMW Group since 1967, employs a workforce of around 18,500 and produces about 1,500 cars per day. The other plant is located in Sindelfingen and was founded by the automotive producer Daimler in 1915. The annual production of this site is estimated to be 424,609 and it employs a workforce of around 25,947.

For this case study the data of the calendar year from 1 January to 31 December 2011 are considered. All data and information are gathered from public records e.g. environmental declarations, webpages and sustainability reports. The data entry and data processing is then carried out by using the developed assessment tools.

According to the data processing process described in chapter 5, the first step of this analysis results in a structured overview including all indicators for each production site. Figure 6.1 and Figure 6.2 illustrate the results.

Comparing different Factories

Company name: **BMW_Dingolfing**
Evaluation period from: **01.01.2011 to 31.12.2011**

Environmental Indicator		Results		Social Indicator		Results		Economic Indicator		Results	
Energy use	total	893916	MWh	Number of working	total	266	-	Net profit margin		6,68	%
	per product	2,60	MWh	accidents	per employee	0,01	-				
Material	total	302640,00	Kg	Safety trainings	total	185	-	Return of capital employed		23,1	%
use	per product	0,88	Kg		per employee	0,01	-				
Freshwater	total	782691	m³	Hazardous materials	total	6847	Kg	Investment in new	total	665	$
use	per product	2,28	m³		per product	0,02	Kg	processes	per product	1937,79	$
Amount of	total	20677,00	Kg	Training and education	total	532800	hour	Investment in staff	total	48,5	$
waste	per product	0,06	Kg		per employee	29	hour	development	per product	141,33	$
GWP	total	111224,00	t	Sickness frequency	total	291375	Days	Expenditures on	total	12,45	$
	per product	0,32	t		per employee	15,75	Days	EHS compliance	per product	36,28	$
AP	total	30,40	t	Employee attrition rate		2,16	%				
	per product	0,00	t	Share of women in workforce		7,40	%				
				Share of women in Management		5,00	%				
				Wages at lowest wage group a year		15114	$				

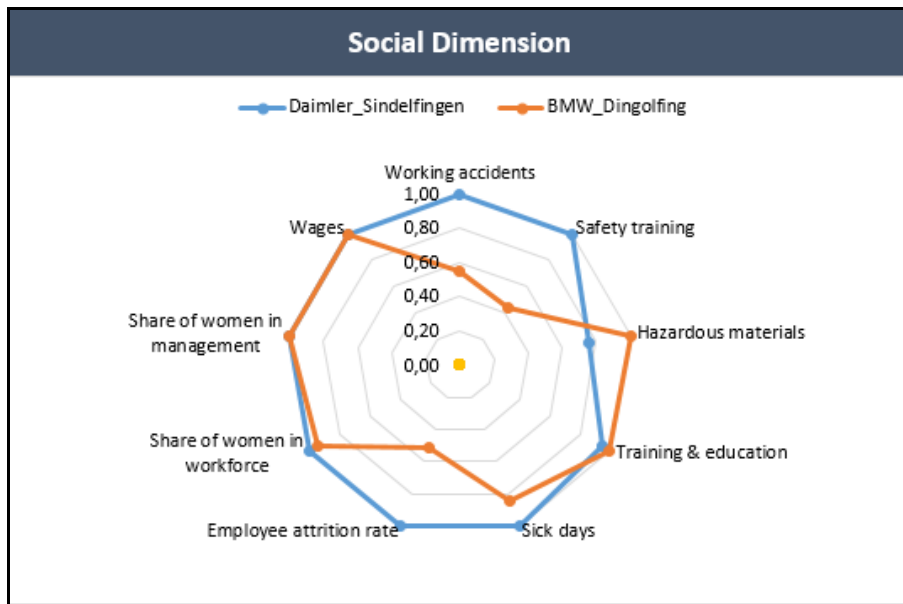**Figure 6.1: Presentation of assessment results for BMW Dingolfing**

Comparing different Factories

Company name: **Daimler_Sindelfingen**
Evaluation period from: **01.01.2011 to 31.12.2011**

Environmental Indicator		Results		Social Indicator		Results		Economic Indicator		Results	
Energy use	total	1143286	MWh	Number of working	total	680	-	Net profit margin		7,63	%
	per product	2,69	MWh	accidents	per employee	0,03	-				
Material	total	306540,00	Kg	Safety trainings	total	114	-	Return of capital employed		19,50	%
use	per product	0,72	Kg		per employee	0,00	-				
Freshwater	total	1165758	m³	Hazardous materials	total	6372	Kg	Investment in new	total	2265	$
use	per product	2,75	m³		per product	0,02	Kg	processes	per product	5334,32	$
Amount of	total	26067,00	Kg	Training and education	total	788788	hour	Investment in staff	total	46,8	$
waste	per product	0,06	Kg		per employee	30	hour	development	per product	110,22	$
GWP	total	200338,00	t	Sickness frequency	total	481316	Days	Expenditures on	total	79,8	$
	per product	0,47	t		per employee	18,55	Days	EHS compliance	per product	187,94	$
AP	total	68,80	t	Employee attrition rate		4,20	%				
	per product	0,00	t	Share of women in workforce		7,00	%				
				Share of women in Management		5,00	%				
				Wages at lowest wage group a year		15114	$				

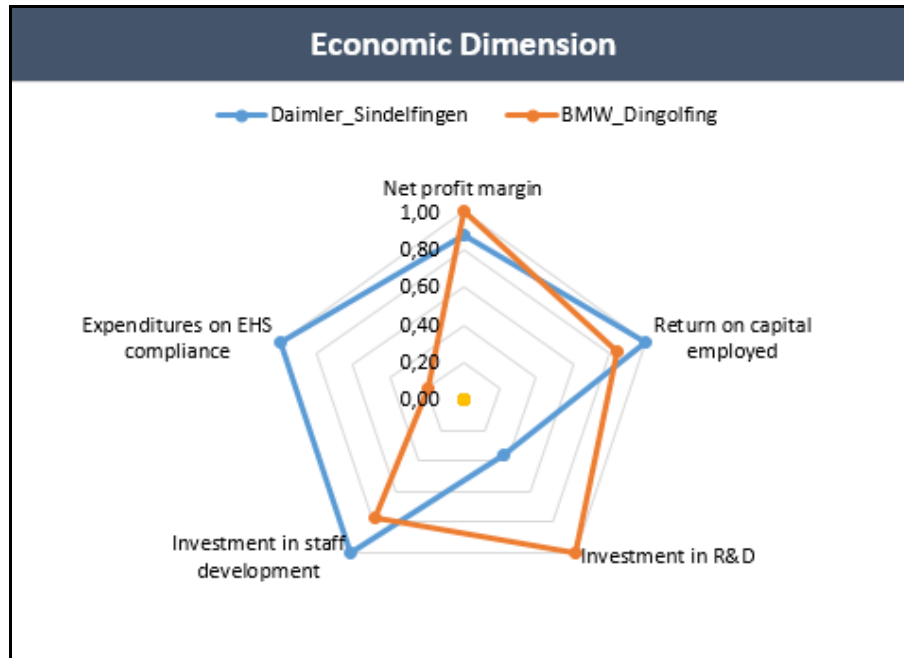**Figure 6.2: Presentation of assessment results for Daimler Sindelfingen**

In a next step of the analysis the results of each indicator are illustrated in a spider chart and are compared for both sites. The results of this comparison are presented in the following three figures. The closer the value is to 0 the better the performance.
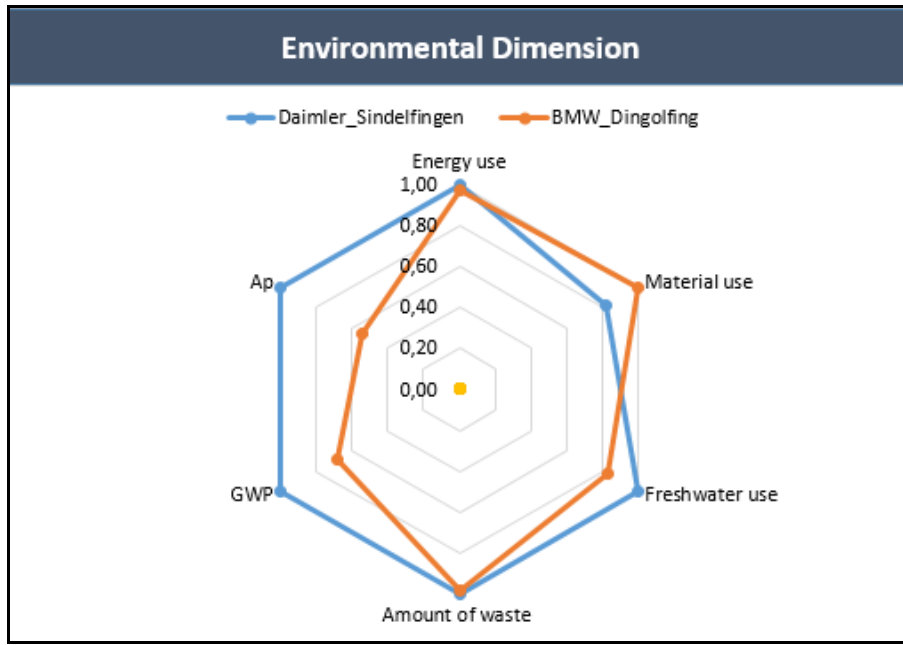
Figure 6.3: Presentation of assessment results by environmental indicators

Figure 6.4: Presentation of assessment results by social indicators

Figure 6.5: Presentation of assessment results by economic indicators

This comparison demonstrates that the BMW plant performs better than the Daimler plant in terms of most environmental indicators, expect for the *material use*. Also it can be determined that the *energy use* and the *waste generation* are rather similar for both sites. With regard to the social dimension it is striking that the BMW plant performs significantly better in terms of *working accidents*, *safety trainings* and *employee attrition rate*. The Daimler plant on the other hand performs slightly better in terms of *hazardous material* and *training and education*. The economic dimension is particularly interesting regarding the two indicators *investment in R&D* and *expenditures on EHS compliance*. While the Daimler plant invests significantly more in R&D, the BMW plant has lower costs in terms of EHS compliance.

In order to make a general statement about the sustainability performance of both production sites, the results of each indicator have to be weighted and combined into a composite index. The results of this process are presented in the following table.

Table 6.1: Sub-indices and overall index for the comparison of the production sites Dingolfing and Sindelfingen

Company	Environment Sub-Index	Social Sub-Index	Economic Sub-Index	Overall Index
BMW Dingolfing	0.87	0.83	0.75	0.81
Daimler Sindelfingen	0.95	0.96	0.91	0.93

It can be seen that the BMW plant Dingolfing performs better in all areas. However, the overall index of 0.81 compared to the index of 0.93 shows that the differences are not as significant and both production plants are in the same range. The results are also visualized in Figure 6.6.
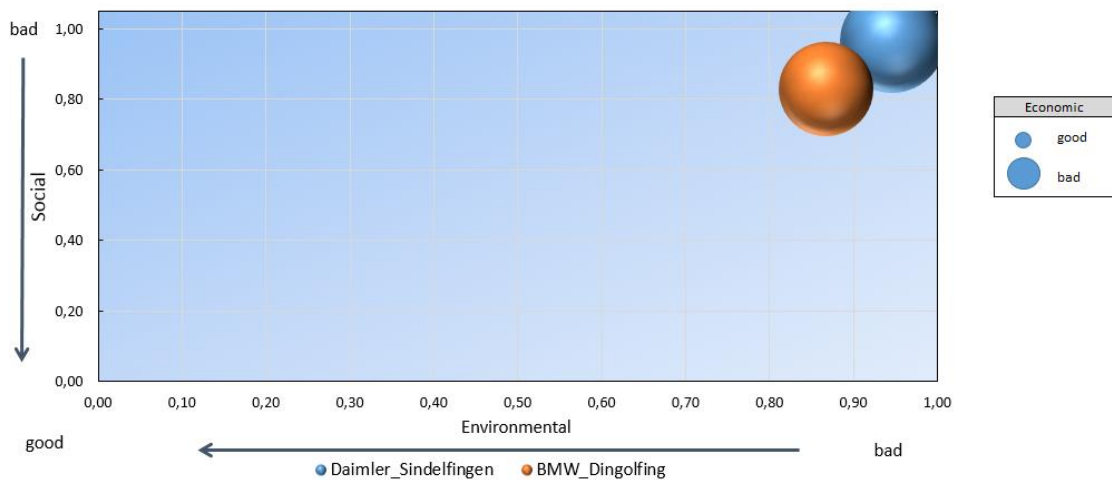
Figure 6.6: Presentation of assessment results by social indicators

Finally, it can be concluded that the comparison of different factories provides clear results and presents them in a comprehensible form. Since BMW is the sustainable leader in the automotive industry, it was expected for the BMW plant to perform better. However, there are also indicators where the Daimler plant achieved better results. This might be interesting for a factory manager of either one of the two companies in

order to improve the performance in the future. On the other hand these results are also interesting for any investor with a focus on sustainable investing. In this case the analysis clearly supports the decision to invest in the BMW plant in Sindelfingen.

6.2   Assessment of a Factory over Time

In this section, the sustainability performance of the company BMW is assessed from 2010 to 2012. It is a leading company in terms of sustainability and has been awarded with several prizes. The BMW Group was named for example best automotive producer in the Dow Jones Sustainability Group Index several times in a row and it is ranked at GRI level A+, which means that BMW meets the maximum requirements detailed by the GRI guidelines.

For this case study the evaluation period for all three periods is again the calendar year from 1 January to 31 December. For the most part the data were taken from the BMW Sustainability Report 2012, because all data in this report were audited and verified by a third party and it is therefore a reliable source. In this case the data includes the 17 main production sites e.g. Landshut, Leipzig and Munich and presents an average over all of them.

After gathering and entering the data for each evaluation period into the computer based tool, the data processing is performed. According to chapter 5 the first step of the data processing results in a structured overview. The following three figures illustrate the results and provide detailed information for each evaluation period.

Comparing different Factories

Company name: **BMW2012**
Evaluation period from: **01.01.2012 to 31.12.2012**

Environmental		Results		Social		Results		Economic		Results	
Energy use	total	2906404 MWh		Number of working accidents	total	4128 -		Net profit margin		24,50 %	
	per product	1,56 MWh			per employee	0,04 -					
Material use	total	522916,13 Kg		Safety trainings	total	4315,00 -		Return of capital employed		23,10 %	
	per product	0,28 Kg			per employee	0,04 -					
Freshwater use	total	3910923 m³		Hazardous materials	total	28106 Kg		Investment in new processes	total	3952 $	
	per product	2,10 m³			per product	0,02 Kg			per product	2122,65 $	
Amount of waste	total	664752,00 Kg		Training and education	total	3133930 hour		Investment in staff development	total	282 $	
	per product	0,36 Kg			per employee	30 hour			per product	151,46 $	
GWP	total	1257226,00 t		Sickness frequency	total	1630490 Days		Expenditures on EHS compliance	total	67 $	
	per product	0,68 t			per employee	15,40 Days			per product	35,99 $	
AP	total	440,90 t		Employee attrition rate		3,87 %					
	per product	0,00 t		Share of women in workforce		14,20 %					
				Share of women in Management		10,00 %					
				Wages at lowest wage group a year		15470 $					

Figure 6.7: Presentation of assessment results for BMW 2012

Comparing different Factories

Company name: **BMW2011**
Evaluation period from: **01.01.2011 to 31.12.2011**

Environmental		Results		Social		Results		Economic		Results	
Energy use	total	3101116 MWh		Number of working accidents	total	3941 -		Net profit margin		24,5 %	
	per product	1,78 MWh			per employee	0,04 -					
Material use	total	635452,63 Kg		Safety trainings	total	1059 -		Return of capital employed		25,6 %	
	per product	0,37 Kg			per employee	0,01 -					
Freshwater use	total	3678738 m³		Hazardous materials	total	27133 Kg		Investment in new processes	total	3373 $	
	per product	2,12 m³			per product	0,02 Kg			per product	1939,329 $	
Amount of waste	total	594791,00 Kg		Training and education	total	2888812 hour		Investment in staff development	total	246 $	
	per product	0,34 Kg			per employee	29 hour			per product	141,4394 $	
GWP	total	1234875,00 t		Sickness frequency	total	1579819 Days		Expenditures on EHS compliance	total	63,1 $	
	per product	0,71 t			per employee	15,75 Days			per product	36,27978 $	
AP	total	431,40 t		Employee attrition rate		2,16 %					
	per product	0,00 t		Share of women in workforce		13,50 %					
				Share of women in Management		9,10 %					
				Wages at lowest wage group a year		15114 $					

Figure 6.8: Presentation of assessment results for BMW 2011

Comparing different Factories				

Company name: **BMW2010**
Evaluation period from: **01.01.2010 to 31.12.2010**

Environmental				Social				Economic			
Indicator		**Results**		**Indicator**		**Results**		**Indicator**		**Results**	
Energy use	total	3334331	MWh	Number of working accidents	total	4458	-	Net profit margin		24,3	%
	per product	2,25	MWh		per employee	0,05	-				
Material use	total	561688,52	Kg	Safety trainings	total	1419	-	Return of capital employed		24,2	%
	per product	0,38	Kg		per employee	0,01	-				
Freshwater use	total	3418816	m³	Hazardous materials	total	24759	Kg	Investment in new processes	total	2773	$
	per product	2,31	m³		per product	0,02	Kg		per product	1872,63	$
Amount of waste	total	564117,00	Kg	Training and education	total	1985422	hour	Investment in staff development	total	179	$
	per product	0,38	Kg		per employee	21	hour		per product	120,88	$
GWP	total	1273493,00	t	Sickness frequency	total	1536793	Days	Expenditures on EHS compliance	total	54,8	$
	per product	0,86	t		per employee	16,10	Days		per product	37,01	$
AP	total	327,90	t	Employee attrition rate		3,87	%				
	per product	0,00	t	Share of women in workforce		13,20	%				
				Share of women in Management		10,00	%				
				Wages at lowest wage group a year		15470	$				

Figure 6.9: Presentation of assessment results for BMW 2010

The next step of the data processing considers the different results for all indicators and compares them with each other for each evaluation period. The results are shown in Figure 6.10, Figure 6.11 and Figure 6.12.
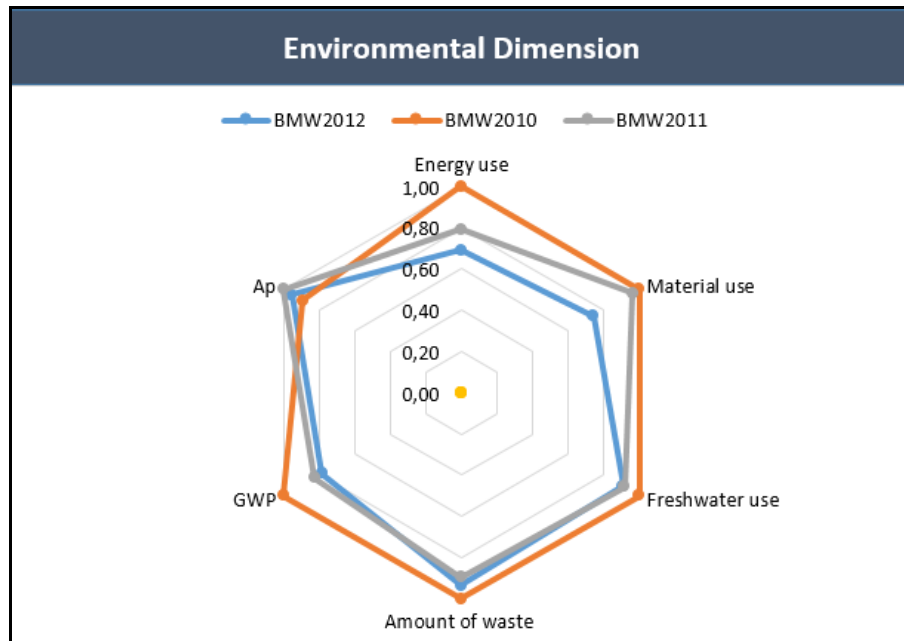
Figure 6.10: Presentation of assessment results by environmental indicators for BMW from 2010 to 2012

Figure 6.11: Presentation of assessment results by social indicators for BMW from 2010 to 2012
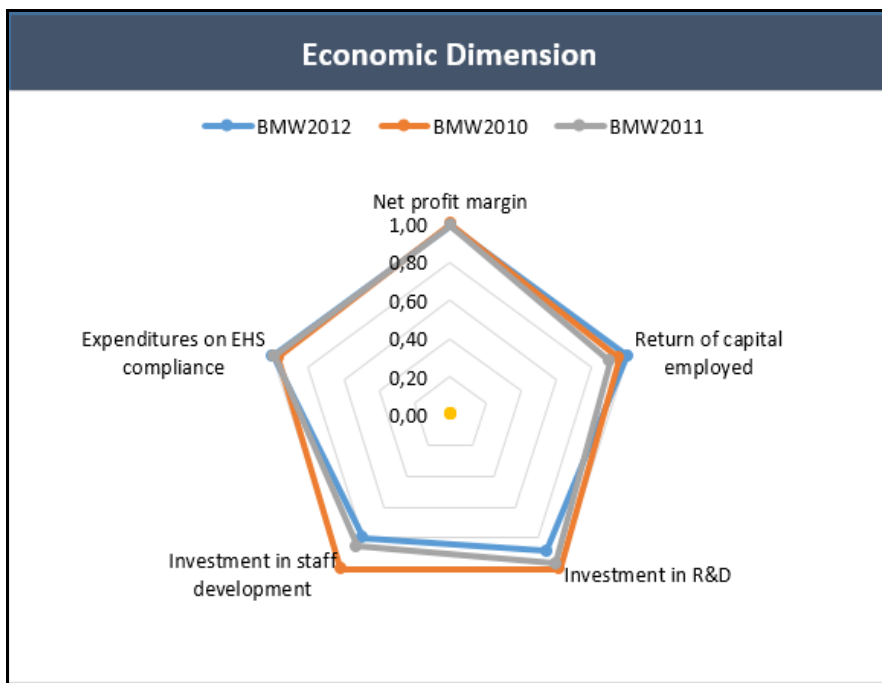
Figure 6.12: Presentation of assessment results by economic indicators for BMW from 2010 to 2012

The spider charts present clearly the development of each indicator. With regard to the environmental dimension it can be seen that the sustainability performance for

almost every indicator improves steadily over time. Only the indicators a*cidification potential* and w*aste generation* show minor differences. Regarding the social dimension it is significant that the e*mployee attrition rate* has increased from 2011 to 2012. Furthermore, it is striking that the s*afety trainings* show a discontinuous development. Additionally, all indicators concerning the economic dimension are rather unremarkable and present only minor differences.

In a next step of this case study it is important to analyze the weighted and combined sub-indices. The indices are presented in Table 6.2.

Table 6.2: Sub-indices and overall index for the comparison of BMW from 2012 to 2010

Company	Environment Sub-Index	Social Sub-Index	Economic Sub-Index	Overall Index
BMW 2012	0,80	0,82	0,94	0,84
BMW 2011	0,87	0,89	0,93	0,89
BMW 2010	0,99	0,96	0,99	0,97

Recalling that the closer the index is to 0 the better the sustainability performance, it can be determined that the environmental and social indices have improved significantly over time. However, the economic dimension shows a minor difference. Here the index for the year 2011 is slightly better than the index for the year 2012. Nevertheless, the overall composite sustainability index indicates again the continuous improvement of the sustainability performance over the last three years. The results are also visualized by the sustainability assessment tool (see Figure 6.13).
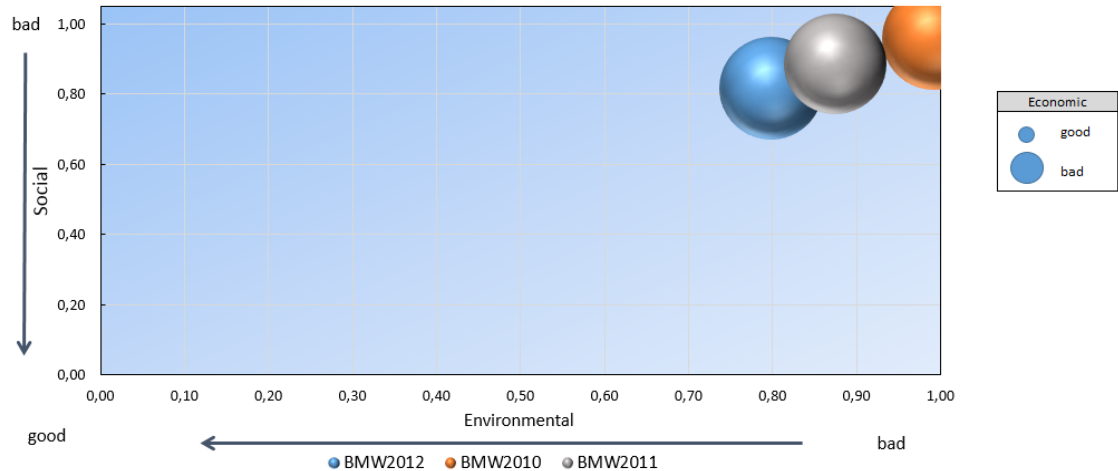
Figure 6.13:   Presentation of assessment results by dimensions for BMW from 2010 to 2012

As a conclusion of this case study it can be summarized that the general development of the sustainability performance of BMW demonstrates a continuous improvement over the last three years. However, it shows also that in the future production managers at BMW should focus more on economic indicators and also on the employee attrition rate.

6.3   Results of the Case Study

The case study has been carried out without any significant complications. The results of the study are clearly visualized and provide detailed information that might be used by factory managers as well as investors to support decisions and to guide future activities.

However, the data collection based on public records required more time than expected. The general sustainability report, a report about the main production sites of a company, offered all data needed for this study. Therefore, the second part of the

case study was completed within 90 minutes, including the data collection, data entry and data processing. The first part of the case study on the other hand was more time consuming. It has been proven more difficult to gather data for an individual production site than for all sites combined. However, the environmental declarations are very useful and provide data for each environmental indicator and also for some social and economic indicators. According to the Eco Management and Audit Scheme (EMAS), a new environmental policy instrument developed by the United Nations, these environmental declarations are required for each production site in order to be certified by EMAS. Therefore, the use and popularity of such environmental declarations is increasing steadily. Other indicators had to be sought in press releases or webpages. Nevertheless, there were still some indicators such as the number of working accidents that had to be derived from the general sustainability report, by calculating the share of the total number of working accidents for the specific production site based on its size. However, this information is not completely accurate.

Overall it can be concluded that data collection for large companies with a focus on sustainability is significantly easier than for small and individual production sites. However, since sustainability is attracting more and more attention it becomes also more important for companies to be certified by environmental audits such as EMAS and therefore they have to publish more figures and data in the future. For now it cannot be guaranteed to find all data on public records, but there is always the option to get in touch with the sustainability contact person in order to gather more information about a specific production site.

CHAPTER 7 - VERIFICATION OF THE USABILITY

Besides testing the developed factory assessment tool on its functional capability and effectiveness, it needs to be tested on its usability as well. In order to get feedback for initial improvements, the tool is tested under real conditions in collaboration with different test users. Thus the first section of the chapter describes the development of a suitable questionnaire. In the second part, the test persons use the questionnaire to evaluate the software based tool. The results are then analyzed and discussed in order to optimize the assessment tool.

7.1 Developing a Usability Questionnaire

Questionnaires are the most frequently used tool for the evaluation of software usability. The goal of the evaluation is to detect weaknesses in the tool and to develop suggestions for improvement. In order to achieve this, the test users have to answer all questions based on their personal experience with the tool.

7.1.1 Usability and ISO Norm 9241

The term usability has been defined by many researchers in many different ways. However, the International Organization for Standardization (ISO) established an official standard on usability. ISO 9241 defines usability as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (p.2). Additionally, ISO 9241 part 10 formulates seven principles regarding the description, design and evaluation of software:

- Suitability for the task

- Self-descriptiveness

- Controllability

- Conformity with user expectations

- Error tolerance

- Suitability for individualization

- Suitability for learning

These principles can only be applied as general guidelines when assessing a software. They are still too vague to be considered as an evaluation instrument on its own.

However, one approach that supports usability assessment according to ISO 9241 is the ISONORM 9241/10 questionnaire. It consist of 35 bipolar items, five for each of the seven principles. The test persons judge each statement with values on a scale from - - - (very negative) to +++ (very positive) (Prümper, Michael 1993).

7.1.2   Structure and Layout of the Questionnaire

Based on the ISONORM 9241/10, a questionnaire for the evaluation of the rapid factory assessment tool is being developed. It consists of the same seven principles and uses the same rating scale. However, since the original ISONORM 9241/10 is usually used for more complex and larger software, certain bipolar items have to be adjusted or simply neglected in order to meet the demands of the rapid factory assessment tool and to decrease the complexity. Thus, the final questionnaire contains only fourteen items instead of thirty five; two for each principle.

The basic layout of the questionnaire is shown in the figure below. Each block contains the name of the principle, the general topic, the bipolar items and a rating scale. The complete questionnaire can be found in the appendix A3.

Error tolerance

Does the tool ensure a minimal rate of errors?

The tool…	Agreement to the statement	The tool…
does not prevent the user from making errors.	- - - - - - - -/+ + ++ +++	prevents the user from making errors.
provides error messages which are difficult to understand.		provides error messages which are easy to understand.
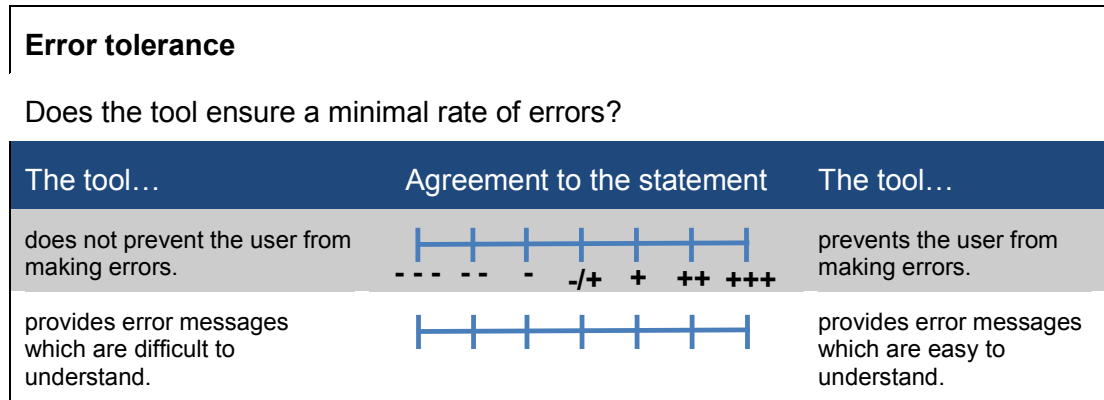
Figure 7.1: Layout of the usability questionnaire

7.2 Testing the Factory Assessment Tool

The tool has to be tested under real conditions in order to obtain meaningful results. As the purpose of the tool specifies that any external user should be able to work with the tool, it is not necessary to test the tool in collaboration with a real factory.

Therefore, the evaluation of the tool is carried out based on the case study from the previous chapter. Each test user is given the task to enter the data of the company BMW for the year 2012 based on its sustainability report. Furthermore, they have to compare the results with the results from the years 2010 and 2011 from the database (see section 6.2). It is assumed that the test user has never seen the tool before and works without further help.

Once the task is completed, the test user has to answer the usability questionnaire. Every question has to be answered based on the personal experience during the case study. For a comprehensive evaluation all questions need to be answered.

7.3   Outcome of the Test

The test has been carried out without any significant complications. Each test user was able to enter the data for each indicator and to analyze them as instructed. It was noticeable that it was fairly time consuming to convert the values from the sustainability report into the right format. Nevertheless, each test user was able to complete the tasks within 45 minutes, including the data entry and data processing. Thus, it is proved that the goal of a *rapid* assessment tool is achieved.

After completing the tasks each test user answered the usability questionnaire. The results of this survey are illustrated in Figure 7.2.
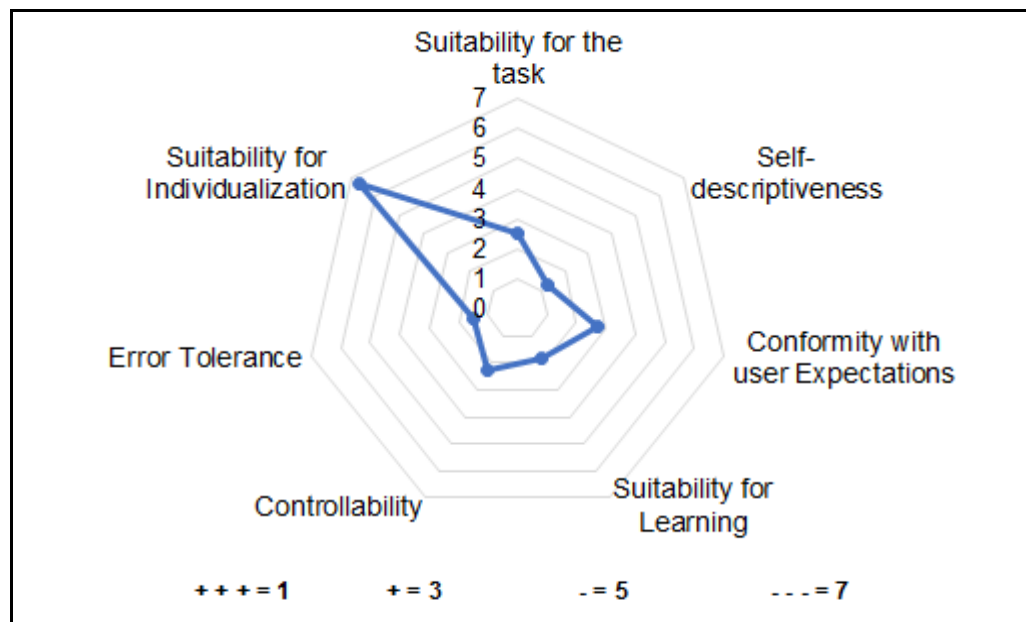
Figure 7.2: Presentation of testing results

The evaluation of the questionnaire demonstrates that the results for six out of seven principles are more than satisfactory. The principles *Suitability for Learning*, *Conformity with User Expectations*, *Self-descriptiveness*, *Controllability*, *Error Tolerance* and *Suitability for the Task* are already in the very positive area. In contrast

to these six principles, the results for the principle *Suitability for Individualization* are rather negative. Since the test users were no VBA-experts they stated that it is very complicated to expand the tool for new tasks or to adapt it to the individual working style.

A subsequent feedback discussion with the test users revealed further suggestions for improvement such as introducing a tabindex and an overview of the different types of industries. In summary, testing the practical case study in collaboration with different test users provided new insights and also possibilities to improve the usability of the tool.

CHAPTER 8 - SUMMARY AND CONCLUSIONS

In the beginning of the study, the basic concept of sustainability as well as the history of its development was presented. Additionally, a comprehensive literature review in the field of sustainability assessment categorized existing sustainability frameworks. It can be concluded that integrated sustainability assessment tools are available at different levels e.g. global, national, company and they are either developed by a company or by a superordinate organization. However, sustainability assessment at factory level is still lagging behind and is not considered sufficiently.

Besides the aspects of sustainability, the study looked also at the factory aspect. In the next phase, the study presented a basic description of factories and illustrated their importance in terms of sustainability, based on energy use and CO_2 emissions. It was pointed out that the manufacturing industry is a main consumer of natural resources and a main producer of adverse environmental impacts. Based on the high responsibility of factories towards their environment, the need for a factory specific sustainability assessment tool was explained. Moreover, it was pointed out that the influence on the environment varies depending on the specific type of industry. In this context, different industrial sectors have been classified as well within this phase.

Based on this situation a framework for a tool at factory level was developed in this research. The framework has a hierarchical structure with the three dimensions of sustainability at the highest level, followed by themes and indicators for each dimension. It was demonstrated that the traditional view in the literature considers three dimensions: social, environmental and economic. This view was adapted for the framework. However, the definition of suitable themes and indicators required more effort. The main sustainability assessment tools that have been identified in the

literature review had to be analyzed and compared in order to derive suitable themes and indicators for the framework.

Furthermore, the framework includes a model to calculate an overall composite index. The development of this index followed various steps. First, the indicators had to be judged whether they support or harm a company's sustainability. Then, they had to be normalized in order to avoid adding up incompatible data sets that can lead to inaccuracies. Therefore different normalization methods were analyzed and selected. It was concluded that a single set of data for one factory cannot be normalized, because currently there is no standardized scale for the assessment values available. However, the method "Distance to a reference" was selected for the case when different companies are compared to each other and the method "Percentage over annual differences" was selected for the case when one factory is being assessed over time. In the next step it was necessary to weight each indicator based on the type of industry in order to obtain a meaningful evaluation of the sustainability performance of factories within each industry. After analyzing and evaluating different weighting methods based on the fulfillment of criterias is was decided to implement the AHP-method. This method provides insights into indicator importance, handles quantitative and qualitative data, is transferable from factory to factory and does not require a large database in order to be calculated. However, since the weighting is based on experts judgment this method is not as objective as methods that are derived from statistical methods. In a next step a formula had to be defined to calculate a sub-index for each sustainability dimension from this model. Finally, all three sub-indices were combined into one overall composite sustainable performance index. In summary, the framework considers three different cases. In the first case a single factory is being assessed; in the second case two or more factories are being compared and in the third case the development of one factory

is being assessed over time. The tool can be used from the external perspective for all three cases and the assessment can be completed rapidly with a minimal time effort.

Based on the given framework, a computer-based tool was developed. Therefore it was necessary to implement the framework into MS Excel by using Visual Basics for Applications. It was pointed out that based on its characteristics VBA is the best fitted solution for the tool.

After implementing the computer based tool, it was then applied to a practical case study in order to demonstrate its application and to test its effectiveness. The first part of this case study focused on the comparison of two production sites. The BMW site in Dingolfing, Germany and the Daimler site in Sindelfingen, Germany. The second part considered the assessment of the BMW Group from 2010 to 2012. The data collection for both cases was based on public records and used the developed sustainability assessment tool for data entering and data processing. It can be concluded that the tool provides clear results and presents them in a comprehensible form. However, the data collection from public records has revealed some difficulties. Smaller, individual production sites without a strong focus on sustainability have not yet published extensive data or figures on this topic.

Finally, the computer based tool was tested on its usability. In order to get feedback for initial improvements, the tool was tested under real conditions in collaboration with different test users. Test users were asked to perform the same case study as mentioned above, by assessing the sustainability performance for BMW in the year 2012 and to compare the results to the years 2010 and 2011. Once the task was completed, the test user had to answer a usability questionnaire. The questionnaire was developed based on the ISO Norm 9241 and modified to meet the needs of the evaluation. As a result of the evaluation, it can be concluded that the tool meets the

goal of a rapid assessment tool. All test users completed the task within 45 minutes. Furthermore, the results of the questionnaire indicated that the tool prevents the user from making errors, is easy to learn, self-descriptive, suitable for the task and easy to control. However, it was also pointed out that it is rather complicated to expand the tool for new tasks or to adapt it to the individual working style.

Finally, it can be concluded that the research objectives of the study were all achieved. It gives an insight into the history of sustainability, reviews and categorizes the current state of sustainability assessment tools, analyses the impact of factories on their environment and classifies industrial sectors. Furthermore, it develops a framework and implements it into a computer-based tool. Finally, it also tests the tool in collaboration with different test users.

However, the larger goal of the study was to fill the gap of a missing sustainability assessment tool at factory level. Theoretically the tool is verified to achieve the goal, but this needs to be confirmed in practice. The tool enables external user such as investors as well as internal users such as factory managers to compare the sustainability performance of different companies or to evaluate the development of a company in terms of sustainability performance. On the one hand this tool supports the investors decision on sustainable investing and on the other hand it may also guide factory managers to think and act in the right direction and to discover possible improvements in order to increase the sustainability metrics related to factory operations. However, there is still potential for future research on this topic, especially when it comes to data collection of small and medium sized factories.

CHAPTER 9 – RECOMMENDATIONS FOR FUTURE RESEARCH

Although ideas for improvement and extensions have been mentioned throughout this study, they shall be summarized at this point. Therefore, the section is divided into two parts. First, the ideas to improve the usability of the developed tool are presented and then the ideas to further improve the assessment framework.

9.1   Usability of the Tool

As the results of the questionnaire pointed out, it is important to improve the *Suitability for individualization.* Since it cannot be assumed that any user is an Excel-expert, a detailed user manual shall be developed. This manual has to instruct the user on how to adapt the tool to the individual working style, to change options and to expand the tool for new tasks.

Minor suggestions on the improvement of the tool such as a tabindex or an overview for the different industrial sectors were already implemented in the latest version of the tool.

9.2   Assessment Framework of the Tool

The model of the tool provided in this work does not offer the calculation of an index for the assessment of a single factory. This is due to the fact that no database or standardized scale for the assessment values is available and the values cannot be normalized. This issue offers potential for further development. One possibility would be to collect data for the leading company in each industrial sector. In case a single factory is being assessed the results can be normalized relative to the benchmark company of the specific industry. The leading sustainability companies could be

identified based on the DJSI. Also, the case study proved that data collection especially for factories with a focus on sustainability is rather easy to accomplish.

Another step of further improvement considers the weighting of indicators by using the AHP method. Since it is a participatory method, the results will be more sophisticated the more experts participate. Therefore the questionnaire should be placed on a webpage where experts have the possibility to evaluate the indicators continuously. The results of the evaluation have to be stored automatically through an interface into a database.

In the future, it might also be possible to place the entire tool on a public webpage. Therefore different users have access to it and they would be able to share a database. The variety of factories in the database would increase and the users have the opportunity to compare the results of different factories with a minimal amount of effort. This may also solve the problem concerning the complicated and time consuming data collection for small and midsize factories based on public records.

APPENDICES

A1: Questionnaire for AHP-method

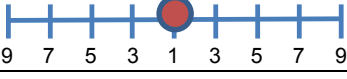### Environmental Dimension

Please do a pair-wise comparison between each pair of indicators, by judging "how important is indicator j relative to indicator i ?". Values are given on a scale from 1 to 9 to show the intensity of preference (see table below). The larger the number, the greater the importance.

Factor of preference	Importance
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely strongly
2,4,6,8	Intermediate values

Example (where *waste* is very strongly preferred over *water* and *energy* and *water* are equally preferred):

Waste generation		Freshwater use
	9 7 5 3 1 3 5 7 9	
Energy use		Freshwater use
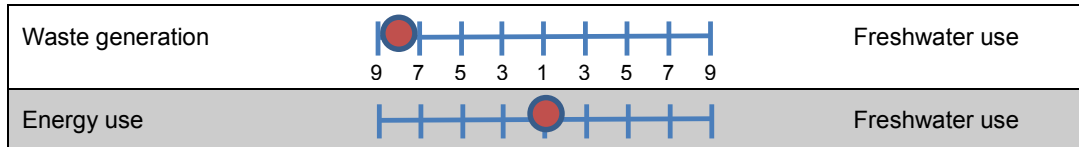
Please fill out the next tables in the same way for each type of industry, by moving the orange dot:

Basic Materials/Resources (Oil & Gas, Chemicals, Basic Resources)

Indicator j	Factor of preference	Indicator i
Energy use		Material use
	9 7 5 3 1 3 5 7 9	
Energy use		Freshwater use
Energy use		Waste generation
Energy use		GWP

Energy use	⊢┼┼┼●┼┼┼⊣	AP
Material use	⊢┼┼┼●┼┼┼⊣	Freshwater use
Material use	⊢┼┼┼●┼┼┼⊣	Waste generation
Material use	⊢┼┼┼●┼┼┼⊣	GWP
Material use	⊢┼┼┼●┼┼┼⊣	AP
Freshwater use	⊢┼┼┼●┼┼┼⊣	Waste generation
Freshwater use	⊢┼┼┼●┼┼┼⊣	GWP
Freshwater use	⊢┼┼┼●┼┼┼⊣	AP
Waste generation	⊢┼┼┼●┼┼┼⊣	GWP
Waste generation	⊢┼┼┼●┼┼┼⊣	AP
GWP	⊢┼┼┼●┼┼┼⊣	AP

Economic Dimension

Please do a pair-wise comparison between each pair of indicators, by judging "how important is indicator j relative to indicator i ?". Values are given on a scale from 1 to 9 to show the intensity of preference (see table below). The larger the number, the greater the importance.

Factor of preference	Importance
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely strongly
2,4,6,8	Intermediate values

Please fill out the next tables for each type of industry, by moving the orange dot (an example can be found at page "environmental dimension"):

Basic Materials/Resources (Oil & Gas, Chemicals, Basic Resources)

Indicator j	Factor of preference	Indicator i
Net profit margin	9 7 5 3 1 3 5 7 9	Return of capital employed
Net profit margin		Investment in R&D
Net profit margin		Investment in staff development
Net profit margin		Expenditures on EHS compliance
Return of capital employed		Investment in R&D
Return of capital employed		Investment in staff development
Return of capital employed		Expenditures on EHS compliance
Investment in R&D		Investment in staff development
Investment in R&D		Expenditures on EHS compliance
Investment in staff development	9 7 5 3 1 3 5 7 9	Expenditures on EHS compliance

Social Dimension

Please do a pair-wise comparison between each pair of indicators, by judging "how important is indicator j relative to indicator i ?". Values are given on a scale from 1 to 9 to show the intensity of preference (see table below). The larger the number, the greater the importance.

Factor of preference	Importance
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely strongly
2,4,6,8	Intermediate values

Please fill out the next tables for each type of industry, by moving the orange dot (an example can be found at page "environmental dimension"):

Basic Materials/Resources (Oil & Gas, Chemicals, Basic Resources)

Indicator j	Factor of preference	Indicator i
Working accidents	9 7 5 3 1 3 5 7 9	Safety trainings
Working accidents		Hazardous materials
Working accidents		Training & education
Working accidents		Sickness frequency
Working accidents		Employee attrition rate
Working accidents		% women in workforce
Working accidents		% women in management
Working accidents		Wages at lowest group
Safety trainings		Hazardous materials
Safety trainings		Training & education
Safety trainings		Sickness frequency
Safety trainings		Employee attrition rate
Safety trainings		% women in workforce
Safety trainings		% women in management
Safety trainings		Wages at lowest group
Hazardous materials		Training & education
Hazardous materials		Sickness frequency
Hazardous materials		Employee attrition rate
Hazardous materials		% women in workforce
Hazardous materials		% women in management
Hazardous materials		Wages at lowest group
Training & education		Sickness frequency
Training & education		Employee attrition rate

112

Training & education	⊢─┼─┼─┼─●─┼─┼─┼─┤	% women in workforce
Training & education	⊢─┼─┼─┼─●─┼─┼─┼─┤	% women in management
Training & education	⊢─┼─┼─┼─●─┼─┼─┼─┤	Wages at lowest group
Sickness frequency	⊢─┼─┼─┼─●─┼─┼─┼─┤	Employee attrition rate
Sickness frequency	⊢─┼─┼─┼─●─┼─┼─┼─┤	% women in workforce
Sickness frequency	⊢─┼─┼─┼─●─┼─┼─┼─┤	% women in management
Sickness frequency	⊢─┼─┼─┼─●─┼─┼─┼─┤	Wages at lowest group
Employee attrition rate	⊢─┼─┼─┼─●─┼─┼─┼─┤	% women in workforce
Employee attrition rate	⊢─┼─┼─┼─●─┼─┼─┼─┤	% women in management
Employee attrition rate	⊢─┼─┼─┼─●─┼─┼─┼─┤	Wages at lowest group
% women in workforce	⊢─┼─┼─┼─●─┼─┼─┼─┤	% women in management
% women in workforce	⊢─┼─┼─┼─●─┼─┼─┼─┤	Wages at lowest group
% women in management	⊢─┼─┼─●─┼─┼─┼─┤	Wages at lowest group

A2: Results of the Weighting Method

Key indicators	Basic Materials/ Resources	Industrials	Consumer Goods	Health Care	Utilities	Technology
Environment						
Energy use	0,27	0,24	0,24	0,25	0,29	0,25
Material use	0,15	0,19	0,19	0,19	0,13	0,19
Freshwater use	0,11	0,12	0,13	0,11	0,12	0,11
Waste	0,12	0,11	0,17	0,18	0,17	0,18
GWP	0,24	0,28	0,20	0,20	0,22	0,20
AP	0,11	0,07	0,07	0,07	0,07	0,07
Social						
Working accidents	0,26	0,21	0,19	0,19	0,12	0,11
Safety training	0,17	0,18	0,11	0,14	0,11	0,10
Hazardous	0,19	0,17	0,11	0,11	0,10	0,09
Training & Education	0,07	0,08	0,13	0,12	0,16	0,17
Sickness	0,06	0,07	0,11	0,08	0,13	0,14
Attrition rate	0,05	0,06	0,08	0,08	0,09	0,10
Women in Workforce	0,06	0,08	0,10	0,11	0,12	0,11
Women Management	0,06	0,08	0,08	0,08	0,08	0,08
Wages lowest group	0,07	0,07	0,09	0,09	0,10	0,10
Economic						
Net profit margin	0,25	0,22	0,26	0,26	0,19	0,20
Return of capital employed	0,29	0,33	0,34	0,34	0,28	0,25
Investment in R&D	0,14	0,16	0,14	0,14	0,25	0,25
Investment in staff	0,14	0,18	0,16	0,16	0,17	0,20
Costs for EHS	0,17	0,11	0,11	0,11	0,11	0,11
Dimensions						
Environmental	0,41	0,33	0,33	0,33	0,33	0,33
Social	0,33	0,33	0,33	0,33	0,33	0,33
Economic	0,26	0,33	0,33	0,33	0,33	0,33

A3:   **Usability Questionnaire**

Please evaluate the factory assessment tool by judging each statement of the questionnaire. Values are given on a scale from --- (very negative) to +++ (very positive).

The goal of the evaluation is to detect weaknesses in the tool and to develop suggestions for improvement. In order to achieve this, please answer every question based on your personal experience.

Suitability for the task

Does the tool support to realize the tasks more effectively and efficiently?

The tool…	Agreement to the statement	The tool…
is complicated to use.	--- -- - -/+ + ++ +++	is not complicated to use.
requires unnecessary input.		does not require unnecessary input.

Self-descriptiveness

Is every step understandable in an intuitive way?

The tool…	Agreement to the statement	The tool…
uses terms, definitions and/or symbols that are difficult to understand.	--- -- - -/+ + ++ +++	uses terms, definitions and/or symbols that are not difficult to understand.
does not offer context-sensitive explanation, which are concretely helpful.		does offer context-sensitive explanation, which are concretely helpful.

Conformity with user expectations

Is the tool consistent with common expectations and habits?

The tool…	Agreement to the statement	The tool…
complicates orientation due to an inconsistent design.	├──┼──┼──┼──┼──┤ - - - - - - -/+ + ++ +++	facilitates orientation due to a consistent design.
provides insufficient insight regarding its current status.	├──┼──┼──┼──┼──┤	provides sufficient insight regarding its current status.

Suitability for learning

Is the effort for learning the tool as low as possible?

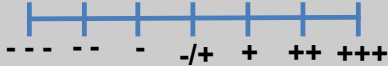| The tool…	Agreement to the statement	The tool…
requires a lot of time to learn.	├──┼──┼──┼──┼──┤ - - - - - - -/+ + ++ +++	requires little time to learn.
cannot be used without previous knowledge or training.	├──┼──┼──┼──┼──┤	can be used without previous knowledge or training.

Controllability

Is the user able to start the sequence and influence its direction?

The tool…	Agreement to the statement	The tool…
forces the user to follow an unnecessarily rigid sequence of steps.	├──┼──┼──┼──┼──┤ - - - - - - -/+ + ++ +++	does not force the user to follow an unnecessarily rigid sequence of steps.
does not support easy switching between individual menus or masks.	├──┼──┼──┼──┼──┤	supports easy switching between individual menus or masks.
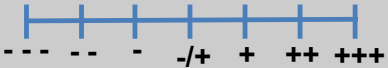
Error tolerance

Does the tool ensure a minimal rate of errors?

The tool…	Agreement to the statement	The tool…
does not prevent the user from making errors.	- - - -- - -/+ + ++ +++	prevents the user from making errors.
provides error messages which are difficult to understand.		provides error messages which are easy to understand.

Suitability for individualization

Does the tool allow customizing according to the task and individual preferences?

The tool…	Agreement to the statement	The tool…
is difficult to expand for new tasks.	- - - -- - -/+ + ++ +++	is easy to expand for new tasks.
is difficult to adapt to the individual working style.		is easily adaptable to the individual working style.

BIBLIOGRAPHY

Brundtland, Gro H.: World Commission on Environment and Development. In: Our Common Future, vol. 42, pp. 8–9.

Cherchye, L.; Moesen, W.; Rogge, N.; van Puyenbroeck, T.; Saisana, M.; Saltelli, A. et al. (2007): Creating composite indicators with DEA and robustness analysis: the case of the Technology Achievement Index. In J Oper Res Soc 59 (2), pp. 239–251.

Cherchye, L.; Moesen, W.; van Puyenbroeck, T. (2004): Legitimately Diverse, yet Comparable: On Synthesizing Social Inclusion Performance in the EU*. In JCMS: J Common Market Studies 42 (5), pp. 919–955.

Davidson, Cliff I.; Hendrickson, Chris T.; Matthews, H. Scott; Bridges, Michael W.; Allen, David T.; Murphy, Cynthia F. et al. (2010): Preparing future engineers for challenges of the 21st century: Sustainable engineering. In Going beyond the rhetoric: system-wide changes in universities for sustainable societies 18 (7), pp. 698–701. Available online at http://www.sciencedirect.com/science/article/pii/S0959652609004156.

Despeisse, M.; Ball, P. D.; Evans, S.; Levers, A. (2012): Industrial ecology at factory level – a conceptual model. In Journal of Cleaner Production 31 (0), pp. 30–39. Available online at http://www.sciencedirect.com/science/article/pii/S0959652612001035.

Deturck, D. M. (1987): The approach to consistency in the analytic hierarchy process. In Mathematical Modelling 9 (3–5), pp. 345–352. Available online at http://www.sciencedirect.com/science/article/pii/027002558790491X.

DJSI (2013): Dow Jones Sustainability Index. Available online at http://www.sustainabilityindex.com/dow-jones-sustainability-indexes/index.jsp/, checked on 13/04/2013.

Donella Meadows, Dennis Meadows Jorgen Randers and William Behrens, III (1972): Limits to Growth. New York: Universe Books.

Dresner, Simon (2002): The Principles of Sustainability. London: Earthscan Publications Ltd.

EICC (2012): Electronic Industry Citizenship Coalition Code of Conduct. With assistance of EICC. Available online at http://www.eicc.info/documents/EICCCodeofConductEnglish.pdf, updated on 12/04/2012, checked on 20/04/2013.

El-Mahgary, Sami; Lahdelma, Risto (1995): Data envelopment analysis: Visualizing the results. In European Journal of Operational Research 83 (3), pp. 700–710. Available online at http://www.sciencedirect.com/science/article/pii/037722179400303T.

EPA (2012): Wastes - Municipal Solid Waste. Edited by U.S. Environmental Protection Agency. Available online at http://www.epa.gov/epawaste/comments.htm, updated on 15/11/2012, checked on 8/06/2013.

Feng, S. C.; Joung, C.-B; Li, G. (2010): Development Overview of Sustainable Manufacturing Metrics. Edited by S. C. Feng, C.-B Joung, G. Proceedings of the 17th CIRP International Conference on Life Cycle Engineering Li. Available online at http://www.sustainelectronics.illinois.edu/NSFworkshop/Reading/Development%20Overview%20of%20Sustainable%20Manufacturing%20Metrics.pdf, updated on 13/05/2010, checked on 2/06/2013.

Global Reporting Initiative (2011): Sustainability Reporting Guidelines. Version 3.1. Edited by Global Reporting Intiviative. Netherlends. Available online at https://www.globalreporting.org/resourcelibrary/G3.1-Guidelines-Incl-Technical-Protocol.pdf, checked on 17/04/2013.

Gluch, Pernilla; Baumann, Henrikke (2004): The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making (5). Available online at http://publications.lib.chalmers.se/records/fulltext/local_2423.pdf, checked on 2/05/2013.

Graedel, T. E.; Allenby, Braden R. (2010): Industrial ecology and sustainable engineering. International ed. Boston: Pearson.

Hermans, Elke; van den Bossche, Filip; Wets, Geert (2008): Combining road safety information in a performance index. In Accident Analysis & Prevention 40 (4), pp. 1337–1344, checked on 11/06/2013.

Hussey, D.; Kirsop, P.; Meissen, R. (2001): Global Reporting Initiative Guidelines. An Evaluation of Sustainable Development Metrics for Industry. In Environmental Quality Management, (Vol. 1), pp. 143–162.

Joung, Che B.; Carrell, John; Sarkar, Prabir; Feng, Shaw C. (2013): Categorization of indicators for sustainable manufacturing. In Ecological Indicators 24 (0), pp. 148–157. Available online at http://www.sciencedirect.com/science/article/pii/S1470160X12002294.

Kölsch, Daniela (2011): Sozioökonomische Bewertung von Chemikalien. Entwicklung und Evaluation einer neuartigen und umfassenden sozioökonomischen Bewertungsmethode, basierend auf der SEEBALANCE® Methode zur Bewertung von Chemikalien unter REACh. Dissertation, Kahlsruhe. KIT, checked on 8/06/2013.

Krajnc, Damjan; Glavič, Peter (2005): How to compare companies on relevant dimensions of sustainability. In *Ecological Economics* 55 (4), pp. 551–563. Available online at http://www.sciencedirect.com/science/article/pii/S0921800904004513.

Labuschagne, Carin; Brent, Alan C.; van Erck, Ron P.G (2005): Assessing the sustainability performances of industries. In Journal of Cleaner Production 13 (4), pp. 373–385, checked on 11/04/2013.

Microsoft (2013): Introducing Visual Basic For Applications. Edited by Microsoft. Available online at http://msdn.microsoft.com/en-us/library/office/aa188202%28v=office.10%29.aspx, checked on 8/07/2013.

Müller, Egon; Engelmann, Jörg; Löffler, Thomas; Strauch, Jörg (2009): Energieeffiziente Fabriken planen und betreiben. Berlin Heidelberg: Springer-Verlag, checked on 27/05/2013.

NACFAM (2009): Sustainable Manufacturing. With assistance of National Council for Advanced Manufacturing. Available online at

http://www.nacfam.org/PolicyInitiatives/SustainableManufacturing/tabid/64/ Default.aspx, checked on 28/04/2013.

Nandagopal, R.; Sankar, A. R.N (2009): WAL-MART'S ENVIRONMENTAL STRATEGY. In Asian Journal of Management Cases (6), pp. 119–133. Available online at http://www.cfsgs.com/uploads/3/6/0/1/3601225/119.pdf, checked on 2/05/2013.

Ness, Barry; Urbel-Piirsalu, Evelin; Anderberg, Stefan; Olsson, Lennart (2007): Categorising tools for sustainability assessment. In Ecological Economics 60 (3), pp. 498–508, checked on 11/04/2013.

OECD (2001): OECD Environmental Indicators. TOWARDS SUSTAINABLE DEVELOPMENT. OECD. Paris (ISBN 92-64-18718-9, 52079 2001). Available online at http://www.oecd.org/site/worldforum/33703867.pdf, updated on 9/01/2002, checked on 27/04/2013.

OECD (2003): OECD Environmental Indicators. Development, Measurement and Use. OECD. Paris. Available online at http://www.oecd.org/environment/indicators-modelling-outlooks/24993546.pdf, updated on 31/10/2003, checked on 27/04/2013.

OECD (2008): Handbook on Constructing Composite Indicators. Methodology and UserGuide. Paris: OECD PUBLICATIONS. Available online at www.oecd.org/publishing/corrigenda, checked on 11/06/2013.

OECD Sustainable Development Studies: Measuing Sustainable Production. Developing Indicators of Energy Efficiency. With assistance of Cecilia Tam. 2008. Available online at http://browse.oecdbookshop.org/oecd/pdfs/product/9708021e.pdf, checked on 28/05/2013.

O'Riordan, Tim (1988): The Politics of Sustainability. In Sustainable Environmental Managment: Principles and Practice.

Parenti, Christian (2012): 'The Limits to Growth': A Book That Launched a Movement. Available online at http://www.thenation.com/article/171610/limits-growth-book-launched-movement#, checked on 2/05/2013.

Prümper, J.; Michael, A. (Eds.) (1993): Software-Ergonomie '93. Die Evaluation von Software auf Grundlage des Entwurfs zur internationalen Ergonomie-Norm ISO 9241 Teil 10 als Beitrag zur partizipativen Systemgestaltung. Stuttgart: Teubner (Berichte des German Chapter of the ACM, 39).

Ranganathan, J. (1988): Sustainability Rulers: Measuring Corporate Environmental and Social Performance. Edited by Sustainable Enterprise Initiative. Washington, DC. Available online at http://pdf.wri.org/sustainability_rulers.pdf, updated on 13/09/2006, checked on 2/06/2013.

Saaty, Thomas Lorci (1980): The analytic hierarchy process. Planning, priority setting, resource allocation. New York: McGraw-Hill.

Saling, Peter; Maisch, Roland; Silvani, Maurizio; König, Natalie (2005): Assessing the Environmental-Hazard Potential for Life Cycle Assessment, Eco-Efficiency and SEEbalance (8 pp). In Int J Life Cycle Assessment 10 (5), pp. 364–371, checked on 30/04/2013.

SAM (2013): Dow Jones Sustainability World Index Guide. Edited by RobecoSAM AG. Available online at http://www.sustainability-index.com/images/djsi-world-guidebook_tcm1071-337244.pdf, updated on 4/04/2013, checked on 18/04/2013.

Satish Joshi (2000): Product Environmental Life-Cycle Assessment Using Input-Output Techniques. In Journal of Industrial Ecology (3), pp. 95–120, checked on 27/05/2013.

Schmidt, W.-P Taylor A. (2006): Ford of Europe's Product Sustainability Index. Edited by 13th CIRP International Conference of Life Cycle Engineering (CIRP International Conference of Life Cycle Engineering, 13th). Available online at http://www.mech.kuleuven.be/lce2006/key2.pdf, updated on 11/05/2006, checked on 1/05/2013.

Seliger, Günther (2007): Sustainability in manufacturing. Recovery of resources in product and material cycles. Berlin; Heidelberg; New York: Springer.

Shaw C. Feng, Che B. Joung (2009): An Overview of a Proposed Measurement Infrastructure for Sustainable Manufacturing. Edited by The 7th Global

Conference on Sustainable Manufacturing. Manufacturing Engineering Laboratory National Institute of Standards and Technology Gaithersburg, Maryland, USA, updated on 12/11/2009, checked on 25/04/2013.

Shaw C. Feng; Che-Bong Joung; Gang Li (2010): Development Overview of Sustainable Manufacturing Metrics. Proceedings of the 17th CIRP International Conference on Life Cycle Engineering, Hefei, China. In Proceedings of the 17th CIRP International Conference on Life Cycle Engineering, checked on 11/04/2013.

Singh, Rajesh Kumar; Murty, H. R.; Gupta, S. K.; Dikshit, A. K. (2007): Development of composite sustainability performance index for steel industry. In Ecological Indicators 7 (3), pp. 565–588. Available online at http://www.sciencedirect.com/science/article/pii/S1470160X06000550.

Srinivasan, Vijay (2011): An Engineer grapples with sustainable manufacturing. In Clean Techn Environ Policy 13 (2), pp. 217–219.

Sustainable Measures (2010). West Hartford, CT. Available online at http://www.sustainablemeasures.com/node/92, checked on 2/06/2013.

Theis, T.; Tomkin, J. (2012): Sustainability: A Comprehensive Foundation. Houston, Texas: Connexions, Rice University. Available online at http://ia600806.us.archive.org/18/items/ost-earth-sciences-col11325/col11325.pdf, checked on 2/05/2013.

U.S Department of Commerce (2007): How does Commerce define Sustainable Manufacturing? With assistance of International Trade Administration. Available online at http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp, checked on 25/04/2013.

U.S. Department of Labor (2012): Workers Memorial Day. Available online at http://www.dol.gov/_sec/media/speeches/20120426_WMD.htm, updated on 26/04/2012, checked on 8/06/2013.

Uhlman, B.; Saling, P. (2010): Measuring and Communicating Sustainability through Eco-Efficiency Analysis. In CEP Magazine (December 2010). Available online at

http://www.basf.com/group/corporate/en_GB/function/conversions:/publish/ content/sustainability/eco-efficiency-analysis/presentations- files/BASF_Presentation_Uhlman_2010.pdf, checked on 30/04/2013.

UNDP (2013): Human Development Reports. With assistance of United Nations Development Programme. Available online at http://hdr.undp.org/en/statistics/hdi/, updated on 2013, checked on 1/05/2013.

United Nations (2007): Indicators of Sustainable Development: Guidelines and Methodologies. Edited by United Nations publication. New York. Available online at http://sustainabledevelopment.un.org/index.php?page=view&type=400&nr= 107&menu=35, updated on 8/01/2008, checked on 17/04/2013.

United Nations (2013): Sustainable Development. United Nations. Available online at http://sustainabledevelopment.un.org/csd.html, checked on 2/05/2013.

Veleva, Vesela; Ellenbecker, Michael (2001): Indicators of sustainable production: framework and methodology. In Journal of Cleaner Production 9 (6), pp. 519–549. Available online at http://www.sciencedirect.com/science/article/pii/S0959652601000105.

Wackernagel, M.; Rees, W. (1996): Our Ecological Footprint. Reducing Human Impact on the Earth. Gabriola Island: New Society Publishers.

Wal-Mart (2006): Wal-Mart Unveils "Packaging Scorecard" to Suppliers. Chicago. Available online at http://news.walmart.com/news-archive/2006/11/01/wal- mart-unveils-packaging-scorecard-to-suppliers, updated on 1/11/2006, checked on 11/04/2013.

Wal-Mart (2012): Sustainability. Available online at www.walmartstores.com/Sustainability/, checked on 2/04/2013.

Wiendahl, H.-P; ElMaraghy, H.A; Nyhuis, P.; Zäh, M.F; Wiendahl, H.-H; Duffie, N.; Brieke, M. (2007): Changeable Manufacturing - Classification, Design and Operation. In CIRP Annals - Manufacturing Technology 56 (2), pp. 783–809, checked on 27/05/2013.

Yang, Taho; Kuo, Chunwei (2003): A hierarchical AHP/DEA methodology for the facilities layout design problem. In European Journal of Operational Research 147 (1), pp. 128–136. Available online at http://www.sciencedirect.com/science/article/pii/S0377221702002515.

Zettlemoyer, A. (2007): Life Cycle Inventory and the Impact to the Wal-Mart Packaging Sustainable Value Network. In International Life Cycle Assessment and Management.

Zhou, Li; Tokos, Hella; Krajnc, Damjan; Yang, Yongrong (2012): Sustainability performance evaluation in industry by composite sustainability index. In Clean Techn Environ Policy 14 (5), pp. 789–803, checked on 11/06/2013.