Preface

This master thesis is the final piece of the master programme Energy and Environmental Sciences which I performed at the Center for Energy and Environmental Studies (IVEM) of the University of Groningen. This thesis was written during an internship at the Innovation and Research department of Shell Global Solutions in Amsterdam as part of a project about source to sink optimization within Shell. During my internship and while writing my thesis I have a learned a lot about source to sink optimization. Furthermore, the internship forced me to approach sustainable development, especially environmental issues, from the (practical) perspective of a multinational, which was refreshing after 2 years of theory at the university.

This thesis would not be of its current quality without the help and support of my supervisors. Therefore, I would like to thank Frank Niele from Shell Global Solutions and Henk Moll and Ton Schoot Uiterkamp from the Center for Energy and Environmental Studies (IVEM) for their direct and indirect contributions to this thesis. Their dedication, ideas and enthusiasm have helped me in developing my ideas and insights and in writing this thesis about environmental indicators for industrial optimization and design. The thesis has an exploratory character and serves as a starting point for incorporation of environmental issues into triple bottom line optimization models for source to sink chains. I hope the proposed *industrial screening and optimization method* can serve as a basis for further studies about environmental impacts of source to sink chains in the future.

Bram Konneman, July 2008
Summary

Companies use standard financial indicators to determine their business success and optimize their business opportunities. However, sustainable development demands for an integrated approach to economic, environmental and social indicators. Although a lot of indicator initiatives are under development, methodology of measuring sustainable development is not standardized. Besides, most indicators that have been developed evaluate either the global, regional or national level (the macro-level) or the plant, project or product level (micro-level), which means that the upstream or downstream effects of a company or “businesses as a whole” are often ignored. This study goes beyond the plant or product level and aims at the industrial system level by attempting to select and translate environmental indicators into business performance indicators for industrial optimization and design. Industrial optimization and design should enable to screen and compare industrial systems (supply chains) on their environmental impacts. The proposed environmental business performance indicators (EBPI’s) from this study in combination with a mathematical optimization model (not part of this study) can serve as a support tool for business decision-making (e.g. adapting and designing supply chains).

In the first phase of this study existing indicator frameworks are reviewed on their potential to contribute to the development of the EBPI's. Indicator frameworks can be distinguished between macro, meso and micro-level frameworks. Macro-system frameworks give good insight in the (global, regional or national) state of the environment, but do not describe environmental indicators and their relation to business in such way that it is possible to directly use them as environmental business performance indicators. Meso-level frameworks focus on the industrial system or on the company level. Although this is on the level required for industrial system optimization, the indicator frameworks mainly focus on dematerialization of business processes (production) instead of decreasing environmental impact directly. Dematerialization in itself does not necessarily decrease environmental impacts and can even lead to environmental impact trade-offs. The most effective way to decrease environmental impacts from businesses is to decrease environmental business pressures through technology, or more precisely, through adaptive innovation. Adaptive innovation is the application of newly invented tools or methods to adapt to macroscopical changes in the physical environment. Environmental business pressures that can be influenced by technology are included in micro-system frameworks (e.g. LCA, EIA). Therefore, this thesis has developed an industrial screening method that is based on LCA pressure indicators and that distinguishes between inherent and non-inherent environmental pressure indicators.

The second phase of this study elaborates upon the industrial screening and optimization method. In the method supply chains are screened on inherent indicators. Inherent environmental indicators measure environmental pressures that are characteristic of a supply chain and that cannot be prevented by best practice technologies of the specific chain. Contrary, non-inherent environmental indicators are both environmental pressures that are not characteristic of a supply chain (but are inherent to other technology chains), as well as environmental pressures that are characteristic of a specific supply chain and
that can be prevented by applying best practice technology of the specific chain. Inherent indicators can than serve as inputs to industrial optimization models that compare multiple supply chains on their environmental impact. Non-inherent indicators can be used to optimize a single supply chain by micro-level methodologies (e.g. LCA or EIA).

Environmental business pressures (both inherent and non-inherent) can be structured by LCA impact categories. These impact categories arrange single business pressures into one impact by scientifically based aggregation methods. This results in a concise number of impact indices that can be used in an industrial optimization model. Basically, all LCA impact categories include business pressures that can be inherent to selected supply chains. However, this thesis makes a distinction between standard and optional impact categories. The distinction is based on the scale of impact instigated by underlying business pressures. Provided that underlying indicators are inherent to the specific technology chain, standard impact categories that should always be included in industrial optimization are land use, freshwater withdrawal, climate change, ozone depletion, acidification, photo-oxidant formation, eutrophication and ionizing radiation. These impact categories are of global or glocal nature. Glocal impacts in this case are local impacts that take place on a global scale, such as land and freshwater use or eutrophication. Environmental business pressures with a local impact can be regarded as optional in the environmental optimization method (e.g. human and ecotoxicity, odour and noise). Exceptions to this rule can be made for, for example, particulate matter, which is an environmental business pressure that falls into the impact category human toxicity. Particulate matter is a perfect example of a business pressure with a glocal impact and should therefore be included as an indicator (if inherent) in the screening and optimization method.

In the final phase of this study, the industrial screening and optimization method has been applied on the Canadian oil sands industry (in the format of the ISO 14040 protocol). Despite the lack of information on some parts of the oil sands chain and although further studies in this field are required, the study has resulted in a representative overview of inherent environmental indicators of the oil sands technology chain. These inherent environmental indicators (together with financial and social indicators) can serve as input to an industrial optimization model of energy systems.
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1. Introduction

Companies use standard financial indicators to determine their business success (Veleva and Ellenbecker, 2001; Krajnc and Glavic 2005a) and optimize their business opportunities. However, sustainable (socio-economic) development demands for an integrated approach to economic, environmental and social indicators. This tripodal approach, better known as the "Triple Bottom Line" or "3P" concept considers social (People), environmental (Planet) and economic (Profit) aspects as the three pillars of sustainable development (Elkington, 1997).

Although a lot of indicator initiatives are under development, methodology of measuring sustainable development is not standardized. There is no textbook that gives a methodology that is generally accepted and applicable across regions and sectors (Hardi and Barg, 1997). Or as Wilson et al. (2007) observe, “there is no consensus regarding the best approach to the design and use of Sustainable Development Indicators. Sustainable Development Indicators are not yet fully matured”. Most of the indicator frameworks are under development and none is applicable as a whole to evaluate sustainable production (Veleva and Ellenbecker, 2001; Krajnc and Glavic, 2005a).

Most indicators that have been developed evaluate either the global, regional or national community level (the macro-system level) (Labuschagne et al., 2005) or the manufacturing site, project or product level (micro-level), which means that the upstream or downstream effects of the firm’s activities (Azapagic and Perdan, 2000) or “businesses as a whole” are often ignored. However, it is key to develop indicators at the industrial level (the meso-level), that is, moving beyond facility boundaries to evaluate impacts throughout the life cycle of a product or a service, for example by Life Cycle Analysis (Veleva and Ellenbecker, 2001). This study will go beyond the product or service level and is aiming at the industrial system level by attempting to select and translate environmental indicators into business performance indicators (referred to as environmental business performance indicators or EBPI’s in this thesis) for industrial optimization and industrial design. In this way it should be possible to screen and compare supply chains or industrial systems on their environmental impacts. It should be possible to incorporate the selected environmental indicators into an optimization model in which environmental impacts of the concerning supply chains are being minimized while profits and social benefits are maximized. The main goal of this thesis is therefore to find suitable environmental indicators for industrial screening and optimization tools (or models) that can support businesses in adapting and designing supply chains or industrial systems.

1.1 Research question and research method

The main research question that will be the core of this master degree thesis is:

*Which environmental indicators are applicable as business performance indicators and how can they be applied in an industrial optimization model for industrial design?*
To answer the main research question this thesis has been split up into five parts. Each separate part will produce its own results and conclusions, which will serve as input to the following parts. Together, the five parts will generate the information to answer to research question. The study consists of the following parts:

- Theoretical background, including definitions of (environmental) indicators and environmental indicator frameworks and the relationship between business and sustainable development (Chapter 2).
- Inventory and analysis of existing environmental indicator(s) (sets) and indicator frameworks (Chapter 3 and 4).
- Selection of indicators and methods that are applicable to industrial optimization and design (Chapter 5 and 6)
- A practical application of selected indicators and methodology on the oil sands industry (Chapter 7).
- Conclusions, recommendations and discussion on the selected environmental business performance indicators, the chosen methodology and their suitability in practice, based on the oil sands case study (Chapter 8 and 9).

1.2 Boundary setting

The inventory of the indicators will be limited to environmental indicators. Other indicators and indicator sets (social and economic) will not be investigated. Besides, the focus of the study is explicitly on ‘authoritative’ institutions and methodologies, because ‘wide acceptance’ is of utmost importance to (multinational) companies (like Shell). Furthermore, a methodology will be described for the incorporation of the selected environmental indicators into an optimization model. However, triple bottom line optimization models themselves will not be subject of this study.
2. Theoretical background

2.1 Business and sustainable development

The last decades, propagated by major man-made environmental disasters like Bhopal (1984) and Chernobyl (1986), the hole in the ozone layer, the increasing pressures on natural resources and the global warming debate, the concept of sustainable development has been increasingly used throughout society. Milestones that mark the sustainability discourse are the book *Silent Spring* by Rachel Carson (Carson, 1962), the Club of Rome’s report *Limits to Growth* (Meadows et al., 1972) and the report of the Brundtland Commission *Our Common Future* (1987), in which the concept of sustainable development was defined as (WCED, 1987):

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

The Brundtland Commission's work provided the basis for the 1992 UN Conference on Environment and development (UNCED) in Rio de Janeiro, also known as the Earth Summit. It was the first world conference in which sustainability issues were discussed. One of the major achievements of the Earth Summit was the Agenda 21, a plan of action for a sustainable future that was adopted by 178 countries. The Kyoto Protocol (1997), the international response to climate change also was result of the summit. Ten years after the Rio summit a second conference, the World Summit on Sustainable Development (WSSD) was held in Johannesburg (2002). In both conferences business had its share, as concern with environmental and social issues emerged well before the Rio Earth Summit (Schmidheiny et al., 1997).

Azapagic and Perdan (2000) have identified three phases in which way businesses responded to environmental issues and subsequently to the concept of sustainable development. Although Azapagic and Perdan only focus on business response, responses to environmental issues and to the concept of sustainable development can also be seen from a broader perspective as to how society has responded to environmental issues.

According to Azapagic and Perdan (2000) the first phase ran from the early 1970s to the mid-1980s and was characterized by a reactive approach to the then emerging environmental issues. Mainly driven by regulation, end-of-pipe solutions were almost the only option considered at that time (Azapagic and Perdan, 2000). Soon, many realized that pollution prevention and cleaner production were more beneficial options than the clean-up approach, not only in terms of environmental performance but also because these options could reduce costs and increase profits. In the second phase (mid-1980s-early 1990s) this view lead to a slow change in response, from a reactive to a more proactive approach to environmental issues. In the third phase (early 1990-present) environmental performance is starting to be integrated into (business) strategy and development. It was also at this time that Stephan Schmidheiny, a Swiss industrialist, founded the Business Council on Sustainable Development (BCSD) to give business a voice in the Rio Conference Forum. He believed that business could act as a catalyst for
change toward the achievement of sustainable development (WBCSD, 2008). Despite the efforts of the council and despite Agenda 21, which offered business and other actors a route map for progress, they both had more to say to governments than to businesses (Schmidheiny et al., 1997). To keep up the momentum after the Rio conference the Council was merged with the World Industry Council for the Environment in 1995 to form the World Business Council on Sustainable Development (WBCSD). The WBCSD brings together leading international companies (about 200 in 2007) and:

*Provides a platform (for companies) to explore sustainable development, share knowledge, experiences and best practices, and to advocate business positions on these issues in a variety of forums, working with governments, non-governmental and intergovernmental organizations (WBCSD, 2008).*

Another top-down business initiative to sustainable development is the Global Reporting Initiative (GRI). GRI was formed by the Coalition for Environmentally Responsible Economies (CERES) and the Tellus Institute, with the support of the United Nations Environment Programme (UNEP) in 1997. Since, the GRI is developing a generally accepted framework for reporting an organization’s economic, environmental, and social performance (GRI, 2007). Nowadays, many companies report about the environment and social issues in sustainability reports according to GRI guidelines. The emergence of communicating sustainability performance to the ”outer world” can also be seen as a characteristic of the third phase (Azapagic and Perdan, 2000).

Shell was one of the front-runners in sustainability reporting. In 1998 Shell started publishing sustainability reports annually of which the first title ”*People, Planet, Profits, an act of commitment*”, matches the ”3P strategy”. The report stated that in order to contribute to sustainable development Shell had to approach business in a different way and that Shell would strive to help to build a better world in which current and future generations enjoy greater economic, social and environmental security (Shell international, 1999). Moreover, Shell was one of the first (energy) companies to acknowledge the relation of human-induced emissions and climate change. In a speech of Chief Executive Jeroen van der Veer (Shell International, 2006):

*“For us, as a company, the debate about whether man-made climate change is happening is over. The debate now is about what we can do about it.”*  

At the end of the 20th century, many multinationals certified their environmental management systems (EMS) under ISO 14000 standards and many others were in the progress of doing so (Rondinelli and Vastag, 2000). Despite ISO standards and initiatives like GRI and the initiatives mentioned in the introduction companies made their own choices regarding the scope and depth of reporting. Of all the companies that reported on environmental performance 62% provided some quantitative data while only 15% of these companies reported on all key issues (OECD, 2001). The lack of a standardized methodology of measuring sustainable development and the lack of consensus regarding the best approach to the design and use of sustainable development metrics within or between businesses in a life cycle (see introduction) approach indicate that a fourth
(implementation) phase of business response to sustainability is necessary in order to fully integrate sustainable development into the performance of businesses or industries.

2.2 Environmental indicators

Different authors define indicators differently and this is not only the case for environmental indicators. There are many ambiguities and contradictions regarding the general concept of an indicator (Gallopin, 1997). A survey by Gallopin (1997) shows the variety of definitions and the abundance in terms of the indicator concept. In the survey an indicator has been defined as variable, parameter, measure, proxy, quantity, index, sub-index, meter, measuring instrument, fraction, value, empirical model and piece of information. Gallopín (1997) concludes that indicators are variables: an operational representation of an attribute of a system, which can be defined in terms of a specific measurement or observation. By using indicators it is possible to capture complex phenomena or systems (like the environment) in a simplified form (Niemeijer and De Groot, 2008).

Segnestam (2002) gives a more schematic representation of the positioning of indicators (see Fig. 1). Indicators, which are derived from data (or parameters), are tools for analyzing change in society (Segnestam, 2002). If two or more indicators are grouped or combined this is called an indicator set. When indicators are aggregated or weighed an index is created. Both indicators and indices or indicator sets can be analyzed and this information can be input to decision-making.

As has been outlined in chapter 1 the ”Triple Bottom Line” principle regards social, environmental and economic aspects as the three pillars of sustainable development (Elkington, 1997). Sustainability indicators can also be divided into these three basics of sustainability. However, this thesis will only investigate environmental indicators. Environmental indicators are indicators that report on the natural environment in the widest possible sense (Niemeijer and De Groot, 2008) or, as given by the UN (1997):

An environmental indicator is a parameter, or a value derived from parameters, that points to, provides information about and/or describes the state of the environment.
As said in the introduction many institutions have been or are developing indicators for different purposes. The main function of many environmental indicators is to provide information about the state of the environment. This information can be used to:

- Support policy- and decision-making (Gallopín, 1997; Hardi and Barg, 1997; Veleva et al. 2001, UN 2007)
- Measure progress towards established goals (EEA, 1999; OECD 2003, UN 2007; Veleva et al., 2001)
- Communicating and raising awareness among the public about the environmental issues and thoughts (Hardi and Barg, 1997; Gallopín, 1997; EEA, 1999, UN 2007, Veleva et al., 2001)

To give more insight in the different indicators relevant for sustainable development and the position of environmental performance indicators a conceptual framework for environmental indicators is given in the next paragraph.

### 2.3 Conceptual frameworks for environmental indicators

There are several *conceptual frameworks* to identify, develop, structure, and communicate environmental indicators (Gallopín, 1997; Segnestam, 2002) and that help clarify what to measure (UN, 2007). Examples include the Input-Output-Outcome-Impact framework, Issue- or Theme-based frameworks, Capital frameworks and Accounting frameworks (Segnestam, 2002; UN, 2007). However, the most commonly used indicator framework (Niemeijer and De Groot, 2008) that has gained international prominence (Gallopín, 1997), is the Pressure-State-Response (PSR) framework developed by the OECD (1991). The PSR framework is based on the work of Friend and Rapport (1989) about the linkages between environmental stresses and responses on the one hand and economic development on the other (an overview of the PSR framework is given in appendix 1). The UN has adapted the PSR framework to the Driving force-State-Response (DSR) framework (UN, 1996) and the European Environment Agency (EEA) eventually refined the framework to the Driving force-Pressure-State-Impact-Response (DPSIR, see Fig. 2) framework (EEA, 1999).

![Figure 2. DPSIR framework (Source: Niemeijer and De Groot, 2008).](image-url)
Driving forces are the underlying factors influencing a variety of relevant variables (Pressure indicators) and can be seen as indirect causes of environmental problems (Niemeijer and De Groot, 2008). Driving force indicators are derivatives from changes in demand and supply and technology, for example change in population growth, or change in production or consumption patterns. In turn, driving forces cause environmental pressures that directly influence or change the (state or health of the) environment. State indicators can be measures of the condition of the atmosphere, water or land or changes in biochemical cycles. Impact indicators describe the effects of the changes of the state of the environment, for example effects on human health, ecosystems or economy. Subsequently, the natural environment or society may develop a response that feeds back on the driving forces, pressures or on the state or impacts (EEA, 1999). These responses can be both positive (intended) or negative (unintended). In case of a positive response the environmental problem will decrease. In case of a negative response the problem will increase or cause other problems that do not essentially have to be environmental.
3. Inventory of existing environmental indicator frameworks

As has been said in the introduction, methodology of measuring sustainable development is not standardized, neither are the indicators about the (national) state of the environment, nor the indicators for sustainable production by companies. On the one hand, many international organizations, countries, agencies and institutes like the United Nations (UN), the Organization for Economic Co-operation and Development (OECD), The World Bank and the European Environment Agency (EEA) have developed and used sustainability indicators to report about the health or "state of the environment". The indicators have been developed to assess sustainability on the global, regional or national level (the macro level), for example for country comparisons (Veleva and Ellenbecker, 2001; Hass et al. 2003).

On the other hand, numerous organizations are developing sets of indicators to assess the progress of companies towards "sustainable production" (the meso-level). Important developments in the field of sustainable production were the foundation of the World Business Council for Sustainable Development and the foundation of the Global Reporting Initiative. Both have developed indicator frameworks aiming at sustainable production. Furthermore, GRI has developed generally accepted guidelines for reporting an organization’s economic, environmental, and social performance (GRI, 2007). Many companies use the guidelines as a basis for their sustainability reporting. Sustainability reports are emerging as a new trend in corporate reporting, integrating financial, environmental, and social performance of the company into one report (Krajnc and Glavic, 2005a; GRI, 2002; KPMG, 2005). Most of them contain broad outlines of topics to report to their stakeholders, including the public. In 2002 more than 3000 corporate environmental, social or sustainability reports had been published on a voluntary basis (GRI, 2002). Another important development in the field of sustainable production was the introduction of environmental management systems such as the ISO 14000 standards, including ISO 14031, which provides a set of sustainability indicators, and EMAS standards (OECD, 2001). Other organizations that have or are developing well-known sustainable production indicator sets are the Center for Waste Reduction Technologies (CWRT) and IChemE (2002) (Krajnc and Glavic, 2005).

Because large numbers of initiatives have been and are being developed it will be impossible to incorporate them all into this study. Therefore a selection of various frameworks has been made, in which a framework is referred to as a structure that includes (a set of) environmental indicators, e.g. environmental (assessment) reports ("state of the environment" reports, sustainable production reports), and (or derived from) scientific methodologies or tools (such as micro-level tools as LCA, LCIA and EIA). The following criteria have been used to select from the various frameworks:

- The indicator framework should include environmental indicators or indicator sets
- The indicator framework should be developed or used by an authoritative (established and accepted) institution and/or
The indicator framework should be widely used within the scientific community.

An overview of the frameworks that have been based on these criteria are given in Table 1. Although, as mentioned above, not all available indicator frameworks available are included in this study, the selected frameworks should provide a representative overview of the different types of indicator frameworks that are available.

Table 1. Selected environmental indicator frameworks.

<table>
<thead>
<tr>
<th>Level of analysis</th>
<th>Initiator</th>
<th>Framework</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>(including indicator set)</td>
</tr>
<tr>
<td><strong>Macro</strong> (global, regional, national)</td>
<td>UNEP</td>
<td>Global Environment Outlook 4</td>
</tr>
<tr>
<td></td>
<td>EEA</td>
<td>Core set of indicators (idem)</td>
</tr>
<tr>
<td></td>
<td>OECD</td>
<td>OECD environmental indicators (Core set of environmental indicators)</td>
</tr>
<tr>
<td></td>
<td>The World Bank</td>
<td>Environmental performance indicators (idem)</td>
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<td></td>
<td>Eurostat</td>
<td>Environmental pressure indicators</td>
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<tr>
<td></td>
<td>UNCS</td>
<td>Indicators of Sustainable Development (CSD Indicators of Sustainable Development)</td>
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<td></td>
<td>WRI</td>
<td>Millennium Ecosystem Assessment</td>
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<td></td>
<td>WWF</td>
<td>Living Planet Report (Living Planet Index, Ecological Footprint)</td>
</tr>
<tr>
<td></td>
<td>Yale University WEF, JRC/EC</td>
<td>Environmental Sustainability Index (idem)</td>
</tr>
<tr>
<td>methodology / tool</td>
<td>Environmental Input-Output Analysis (EIO)</td>
<td></td>
</tr>
<tr>
<td><strong>Meso</strong> (sustainable production)</td>
<td>ISO</td>
<td>ISO 14000 Environmental Management Systems (ISO 14031 Environmental Performance Evaluation)</td>
</tr>
<tr>
<td></td>
<td>GRI</td>
<td>Sustainability reporting guidelines (Environmental Performance Indicators)</td>
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<td></td>
<td>WBCSD</td>
<td>Eco-efficiency indicators</td>
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<tr>
<td></td>
<td>CWRT/BRIDGES</td>
<td>BRIDGES to Sustainability (Sustainability Metrics)</td>
</tr>
<tr>
<td></td>
<td>IChemE</td>
<td>The Sustainability Metrics (Sustainable Development Progress Metrics)</td>
</tr>
<tr>
<td>methodology / tool</td>
<td>Material Flow Accounting (MFA)</td>
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<tr>
<td>methodology / tool</td>
<td>Environmental Impact Assessment (EIA)</td>
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<tr>
<td>methodology / tool</td>
<td>Life Cycle Assessment (LCA) (Eco-indicator 99)</td>
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<tr>
<td>methodology / tool</td>
<td>Life Cycle Impact Assessment (LCIA) (Eco-indicator 99)</td>
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<tr>
<td>methodology / tool</td>
<td>Material Input Per Unit of Service (MIPS)</td>
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4. Analysis of environmental indicator frameworks

In this section the selected frameworks in Table 1 are analyzed on their suitability for evaluating environmental performance of businesses (paragraph 4.1-4.3) by using a refined DPSIR framework. This section introduces the refined DPSIR framework and concludes with the proposal of matching environmental business performance indicators (potential) EBPI's (paragraph 4.4.).

4.1 Driving force indicators

Focusing on the relationships between business and the environment, driving force indicators in the DPSIR framework are derivatives from consumption, production and technology. “Driving force focused” options to decrease environmental pressure can be derived from the IPAT formula, which was developed by Ehrlich and Holdren (1971). The I=PAT formula represents environmental impact, (I), as the product of three variables; population (P), affluence (A) and technology (T). Impact in this case can is comparable to environmental pressures in the DPSIR framework. Furthermore, population growth will increase environmental pressure (or impact in the formula) ceteris paribus. In the formula affluence refers to produced or consumed goods (Chertow, 2001), which means when consumption patterns change environmental impact changes ceteris paribus. Technology refers to the processes used to obtain resources and transform them into useful goods, including environmental pressure (e.g. emissions) per product unit.

Recently, the IPAT formula was refined to the ImPACT formula by Waggoner and Ausubel (2002), in which environmental impact is the product of population (P), affluence (A), consumption (C) and technology (T). They state that A (affluence) gives the income or the economic muscle for the population to use. Moreover, they have added consumption (C) to the formula, which stands for consumption (or choice), or, as maintained by Waggoner and Ausubel intensity of use. Consumers lever C as they decide to employ more or less of their economic muscle on the product that will eventually impact the environment (Waggoner and Ausubel, 2002). In both the IPAT and ImPACT formulas, technology (T) can be regarded as an environmental efficiency coefficient. Ceteris paribus, more consumable goods per environmental impact or less environmental impact per consumable good can be achieved by reducing T, or in other words, by a more environmentally efficient technology. According to Waggoner and Ausubel (2002) engineers and industry can affect environmental impact by inventing, perfecting and deploying technology.

In Figure 3 the ImPACT formula is integrated in the DPSIR framework, in which not the impact as in the ImPACT formula, but the driving forces of the DPSIR framework are the product of population, affluence, consumption and technology (PACT). The product of these driving forces results in the character and magnitude of the environmental pressures. Figure 3 illustrate the refined DPSIR framework with global warming as an example. In case of global warming, the driving forces consist of the product of population (P), per capita GDP (A), energy consumption per unit GDP (C) and CO₂ emissions per unit of energy consumption (T). Together they determine the total quantity
of CO₂ emissions (the environmental pressure $P$), which in turn causes changes of CO₂ levels in the atmosphere ($dS =$ change of the state of the environment) and consequently could lead to for example sea level rise ($I =$ impact).

$$D = P \times A \times C \times T = P \Rightarrow \Delta S \Rightarrow I \Rightarrow R$$

Figure 3. IPAT formula integrated in DPSIR framework including an example of Global Warming.

*Sustainable production* indicator frameworks (Table 1) like ISO 14031, GRI sustainability reporting indicators (GRI 2007), WBCSD eco-efficiency indicators (Verfaillie and Bidwell, 2000), CWRT/BRIDGES sustainability metrics (Tanzil et al., 2003) but also methodologies such as Material Input per Unit of Service (MIPS) and Material flow Accounting (Wrisberg et al., 2002) are focusing on decreasing environmental impact by using less materials, water, energy and/or land in production processes. Decreasing driving forces is also the main idea in the Factor Four (Weizsäcker et al., 1997), Factor Ten (Factor 10 Club, 1994) and Factor X (Reijnders, 1998) approaches. Both sustainable production indicator frameworks and Factor X approaches advocate the dematerialization of production processes by decreasing resource intensities by a factor $x$ (factor differs per approach). However, by focusing on dematerialization indicators (like material and energy use) it is not directly clear what environmental pressures these driving forces instigate or what environmental impact they cause or decrease. Therefore by reducing driving forces exclusively without understanding of further impacts it is not clear how much and what kind of environmental impacts are reduced. For example, when material use in production process $A$ is reduced by 20% there will be a higher probability that the environmental impact of the process will decrease, however this is not necessarily so. Reducing material intensity might even lead to other detrimental environmental side effects, like higher land use or energy intensity, although impact from higher energy intensity can be counterbalanced by using renewable energy sources like wind or solar power. Contrary, using renewable energy sources might create other environmental impacts such as impacts from land use change. In other words, reducing material and energy should not be an aim in itself. It is the environmental impacts from energy use that need to be reduced.

Therefore, this study will distinguish between resource efficiency and impact reduction potential of technologies. In this thesis impact reduction potential is regarded as the potential reduction of overall environmental impact of a business or source-to-service-to-sink technology chain without causing unintended trade-offs, side effects. In order to develop effective (business) responses to reduce environmental impacts it is of high importance to investigate their underlying environmental pressures.
By reducing environmental pressures through inventing, perfecting and deploying environmental friendly technology businesses can directly decrease impacts on the environment. In this way consumption can possibly remain on the same level, provided that the present linear economy can be turned into a circular economy. The Circular or Closed Loop Economy concept organizes economic activities into a feedback process of ‘resources-production-regenerated resources’ to reduce negative impacts on the natural environment to a minimum (Boulding, 1966). The circular economy is opposing the concept of a Linear Economy in which industrial society’s linear ‘throughput’ of material and energy use up resources and accumulates waste and emissions (Frosch and Gallopoulos, 1989; Graedel, 1996). When impacts on the natural environment cannot be reduced to a minimum through the application of impact reduction technologies it might also be necessary to reduce the other driving force variables (population, affluence and consumption).

4.2 Pressure, State and Impact indicators

Driving forces cause environmental pressures that directly cause environmental impact on the (state or health of the) environment. Although the ISO, GRI, WBCSD and CWRT/BRIDGES sustainable production frameworks mainly focus on driving forces, they also include some pressure indicators. The frameworks include ozone depleting emissions and greenhouse gas emissions as pressure indicators and mention another few like waste and water discharge, number of spills and toxic releases. However, the relations between these pressure indicators and their impact on the state of the environment are not covered in depth.

Macro-system analyses and indicator frameworks like the UNEP Global Environment Outlook (UNEP, 2007), the OECD programme on environmental indicators (OECD, 2007), EEA core set of indicators (EEA, 2005), The World Bank environmental performance indicators (Segnestam, 1999), Eurostat environmental pressure indicators (Eurostat, 1999), the UNCSD Indicators of Sustainable Development (UNCSD, 2007) and the Millennium Ecosystem Assessment (WRI, 2005) and also Environmental Input-Output Analysis (Wrisberg et al., 2002) provide a broader range of environmental pressure indicators and use DPSIR, DSR and PSR frameworks to describe causal chains of environmental problems. Macro-system pressure and impact indicators are applicable to macro-level analysis (e.g. country comparison), but the indicators are only partially suitable as business performance indicators. EBPI’s should be based on the relationship between industrial processes and their environmental pressures in such way that industrial processes (or supply chains or source-to-service-to-sink pathways) can be compared and optimized from an environmental perspective. Though, industrial processes are not explicitly described in macro-frameworks. This requires more in depth knowledge of industrial systems that is not available from the macro-system frameworks. In other words the resolution of the macro frameworks is too low compared to the level of resolution needed for industrial optimization and industrial design. In order to zoom in on industrial systems a more sophisticated system of business pressure indicators is required. Life Cycle Assessment and Life Cycle Impact Assessment provide such a sophisticated system.
LCA is developed for comparison of the environmental impacts along the life cycle of products (Hofstetter, 1998). LCA methodology is based on causal chain networks, or in LCA terms cause-impact networks or impact pathways (Udo de Haes et al., 2002). Basing their causal chains on state of the art scientific knowledge of environmental mechanisms (USEPA, 2000), LCA provides extensive lists of substances (in DPSIR terms these would be regarded as pressure indicators) and their (potential) environmental impact. These lists can serve as checklists to select environmental business pressure indicators for specific source-to-service-to-sink chains. Furthermore, this thesis makes use of an industrial screening level method that distinguishes between inherent and non-inherent environmental (pressure) indicators (see Box 1) of the specific source-to-service-to-sink chains.

On the industrial systems screening level inherent environmental indicators can be used as EBPI’s for industrial optimization and industrial design (between and of multiple source-to-service-to-sink chains). Both inherent and non-inherent indicators can be used for optimization within a single source-to-service-to-sink chain, for example the minimization of specific environmental pressures from a single building block. In the example of Chinese coal fired power plants in Box 1, the old fashioned (and more polluting) technology can be replaced by modern (European) technology. This will reduce the environmental pressure from the electricity generation technology chain of coal, but will not reduce inherent environmental pressures from the coal chain (e.g. land use). These can only be avoided or reduced by switching to another supply chain configuration, in this case another electricity generation mode. Optimization of single supply chains is not part of the industrial screening and optimization method, but can be included in micro-level methods, such as (plant or product level) LCA.
Box 1. Inherent and non-inherent environmental indicators

*Inherent environmental indicators*: measure environmental pressures that are characteristic of a source-to-service-to-sink chain and that cannot be prevented by applying best practice technologies in building blocks of the specific chain (Fig. 4).

An example can be taken from electricity generation from coal. If electricity is generated land use change (disturbance) from coal surface mining operations is inherently connected to the electricity generation technology chain of coal. Land use change (and related impacts) can only be avoided by switching to another configuration (Fig. 4) of the coal technology chain (e.g. underground coal gasification) or switching to another electricity generation mode (e.g. solar power).

*Non-inherent environmental indicators*: are both environmental pressures that are not characteristic of a source-to-service-to-sink chain (but are inherent to other technology chains), as well as environmental pressures that are characteristic of a specific source-to-service-to-sink chain and that can be prevented by applying best practice technology in building blocks of the specific chain.

Again an example can be taken from electricity generation from coal. All environmental pressures that are not related to the coal electricity generation chain are regarded as non-inherent. Besides, coal fired-power plants, in for example China, use old fashioned technology that is more polluting than the (modern European) best practice technology. This ‘surplus’ pollution can also be regarded as non-inherent.

A *Best practice technology chain* is the optimum (best practice) configuration of building blocks of a specific S2S2S chain, with the building blocks consisting of separation and conversion technologies (figure 4). There is, however, no permanent best practice technology as people keep on perfecting existing and inventing new technologies.

![Figure 4. Supply chain configurations.](image)
4.3 Response indicators

There are several ways in which the natural environment or society might respond to environmental impact, either through changing driving forces, pressures, state or impacts. Human responses to environmental problems can roughly be categorized as in Figure 5.

As been described in the preceding paragraphs, the most effective way of reducing environmental problems is preventing them from occurring, that is mitigating the size of the environmental pressure (P). This can be achieved by reducing the four driving force parameters (population, affluence, consumption and technology). However, since the character of the parameters differs, the responses to reduce them also differ. Response to mitigate environmental pressures can be subdivided into responses through adaptive innovation and responses that are grouped as human behavioral responses (Fig. 5). Adaptive innovation is the application of newly invented tools or methods to adapt to (or in this case prevent) macroscopical changes in the physical environment (Niele, 2005). Adaptive innovation directly works on the technology (T) variable of the driving forces depicted in Figure 5. This is also the variable on which business has major impact. Through adaptive innovation businesses can reduce environmental pressure by inventing, perfecting and deploying (more) environmental friendly technologies. Examples of adaptive innovation to reduce environmental pressures (e.g. greenhouse gas emissions) that cause global warming are Carbon Capture and Sequestration (CCS) or the usage of solar power (in a CO₂ neutral way) instead of using fossil fuels. Businesses have no direct influence on the other driving force variables (population, affluence and consumption), which are largely determined by human behavior (socio-economic factors), such as consumer behavior and purchasing power. These driving forces can be influenced on a higher (e.g. governmental or international regulation and legislation) or lower level (people power) than the company or industrial system level.

The opposite of mitigation-focused responses are responses that adapt to impact (I) on the environment (see Fig. 5). The actual pressures are present already, however, the receiving body (either natural or human) adapts to the new environment that is created by the environmental pressure. Examples of adaptation that work on I include the raising of the dikes to prevent flooding induced by global warming (which is in turn, caused by greenhouse gas emissions) and the conservation of natural habitats (e.g. to protect biodiversity) In theory it is possible to restore the state of the environment to its initial state before the impact. This can be achieved by cleaning up pollution (spills). In theory it
is even possible to adapt the state of the environment to reduce environmental impact, for example through geo-engineering. Geoengineering is the intentional large-scale manipulation of the (state of the) environment to reduce undesired anthropogenic environmental impacts (Keith, 2000). An example given by Wigley (2006) is the injection of aerosols or aerosol precursors as sulfur dioxide into the stratosphere to provide a negative forcing of the climate system and consequently offset part of the positive forcing due to increasing greenhouse gas concentrations. However, adaptation and manipulation of the state of the environment, especially geo-engineering, should be seen as a last remedy since there are too many (sometimes unknown) risks involved in geo-engineering. The risks include enormous costs or as MacCracken (2006) puts it: "Geoengineering of climate change would be similar to the costs of ending all dependence on fossil fuels.” However, an even bigger risk will be the unanticipated (unknown) environmental side effects. Geoengineering may result in even worse (environmental) consequences than the changes brought about by ignorance of the anthropogenic influences on Earth's climate (MacCracken, 2006). Because of the high and in some cases unknown risks geoengineering is not seen as a viable solution to environmental problems and is therefore not included in this study and also left out of Figure 5.

In most macro-system indicator frameworks (Table 1) responses are included. The macro-system frameworks do not make a distinction in response-ability (the ability of different actors to respond to environmental problems) as is depicted in Figure 5. The response indicators in most cases have a general character. The OECD (2007) mentions for example energy intensity and economic and fiscal instrument as responses to climate change and water prices and user charges for freshwater scarcity. Because of the general and often policy focused character of the response mentioned in macro-system frameworks they are less suitable for business or industry. The response of business, which should be focused on technical adaptation to environmental problems, should be stated more precisely in order to obtain maximum decrease of environmental pressure (see also Fig. 5). As been described, sustainable production frameworks mainly respond through increasing resource efficiency of technologies, however, focusing on impact reduction potential of technologies is a more effective way of reducing environmental pressures from businesses. LCA and LCIA give more insight in the relation of pressure from a process or a product and (potential) environmental impact to develop effective responses to environmental pressures from the specific process or product. Therefore, LCA/ LCIA will serve as the base methodology for selecting EBPI’s for optimizing source-to-service-to-sink (technology) chains.

4.4 Conclusion of the inventory of indicator frameworks

Environmental indicator frameworks can be clustered by their "level of analysis” (see Fig. 6). Indicator frameworks initiated by international institutions like UNEP, EEA, The World Bank, Eurostat, UNCSD, WRI and WWF (Table 1) give good insight in the different DPSIR categories of macro-systems (global, regional and national systems) and on describing the state of the environment. However, the frameworks do not describe environmental problems and environmental indicators and their relation to business
processes in detail or in such way that it is possible to directly use them as environmental business performance indicators (EBPI’s). Therefore, the resolution of the frameworks is too low to directly derive EBPI’s for industrial optimization and design.

Industrial systems are situated on the meso-level. Frameworks that focus on the meso-level are the sustainable production frameworks (Table 1) initiated by ISO, GRI, WBCSD, CWRT/BRIDGES and IChemE. Although the resolution of indicator sets is on the level of industrial systems (neither too high nor too low detail level), the focus of the indicator frameworks is mainly on dematerialization. However, the most effective way to tackle environmental problems from a business perspective is to focus on environmental pressures, because this is the most direct linkage of business processes (source-to-service-to-sink technology chain) to environmental problems. Environmental pressures can be subdivided into inherent and non-inherent environmental indicators. Except for the IChemE Sustainability Metrics (2004), sustainable production frameworks do not or provide a very limited set of environmental pressure indicators that are or can be related to specific business processes.

Frameworks that use a high resolution, like EIA, LCA and LCIA mainly focus on the project, plant or product level (clustered as micro-system frameworks in Fig. 6). They offer extensive lists of (potential) business pressures. The industrial screening and optimization method that is described in this thesis uses these lists and adds a distinction

<table>
<thead>
<tr>
<th>Framework focus (classified by DPSIR category)</th>
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<tbody>
<tr>
<td>D</td>
</tr>
<tr>
<td>macro (global/regional/national)</td>
</tr>
<tr>
<td>meso (industrial system)</td>
</tr>
<tr>
<td>micro (project/plant/product)</td>
</tr>
</tbody>
</table>

Figure 6. Environmental Indicator frameworks and their level of analysis and position in the DPSIR conceptual framework.
between inherent and non-inherent environmental business pressures of selected technology chains. In this method chains can be optimized on their inherent indicators.

It can be concluded from the inventory and analysis of the selected frameworks that, although the frameworks incorporate environmental indicators into business in various ways, as far as is known to the author, none of these frameworks have used or developed environmental (pressure) indicators for industrial optimization and industrial design. The framework that comes closest is the IChemE Sustainability Metrics (IChemE, 2004). The ”gap” between the macro-system indicator frameworks and the micro-level indicator frameworks is also supported by the work of Hofstetter (1998) in which the positioning of several environmental decision support tools is investigated (see Fig. 7). In the figure industrial optimization and design of supply chains through environmental indicators is at the same level as Technology Assessment (TA). Technology Assessment provides information about a specific technology and its connections to economic, social, political and environmental systems (adapted from Ludwig, 1997). However, since TA lacks sufficient methodology (Ludwig, 1997) it actually uses instruments as LCA, EIA and Environmental Management Systems (EMAS) to analyze environmental impact. The industrial screening level methodology described in this study could therefore be a very useful addition to the concept of Technology Assessment, because as been stated in the preceding paragraphs, none of the existing environmental indicator frameworks used or developed environmental indicators or applicable methodology for industrial optimization and industrial design of source-to-service-to-sink chains.

Because of the absence of well-founded EBPI’s for industrial optimization and industrial design this study will provide an industrial screening level method that distinguishes between inherent and non-inherent environmental pressure indicators of a specific source-to-service-to-sink technology chain. The inherent environmental indicators serve as EBPI’s for optimization and design of supply chains and are deducted from micro-level frameworks (indicated by the arrow in Fig. 6). Eventually, optimization of EBPI’s and response through adaptive innovation should result in a lower environmental impact of the specific business or source-to-service-to-sink chain.
Figure 7. Positions of decision support tools in two dimensions (source: Hofstetter, 1998) (Vertical axis: level of analysis; horizontal axis: dimension of analysis).
5. Environmental indicators for industrial screening and optimization

To effectively target environmental impacts and underlying pressures, businesses should have knowledge about the pressure-state-impact chains of environmental problems. When these causal chains are known, environmental (pressure) indicators from source-to-service-to-sink (technology) chains can be derived and subdivided into inherent and non-inherent indicators. LCA methodologies describe and use stressor-impact chains that are similar to pressure-state-impact chains, in which an environmental stressor is comparable to an environmental pressure from the DPSIR framework. These stressor-impact chains describe environmental mechanisms and draw connections between stressors and items that are potentially affected, such as human health or the natural environment (Udo de Haes et al., 2002). In this chapter LCA methodology is described in paragraph 5.1. Consequently, part of this methodology, that will be the core of the industrial screening and optimization method, will be described in more detail in paragraph 5.2.

5.1 The ISO LCA protocol

Figure 8 includes three examples of stressor-impact chains and corresponding LCA terminology. The stressor-impact chain is part of a fixed LCA protocol (ISO 14040) established by the International Organization for Standardization (ISO), which contains 4 phases; goal and scope definition; inventory analysis; impact assessment and interpretation (ISO, 1997, see also Appendix 2).

![LCA stressor-impact chains including LCA terminology. Based on: Udo de Haes et al. (1999) and Lee and Inaba (2004).](image)

The first phase, goal and scope definition, serves to define the purpose of the study and to describe the system studied. In case of industrial optimization this can include the selection of several source-to-service-to-sink (technology) chains which will be optimized against each other.

Inventory, the second phase consists of data collection on environmental stressors (or environmental pressures) that are connected to the process in the life cycle of a product or
process (Udo de Haes et al., 2002), for example emissions. An inventory is also needed in the industrial system screening method. In this phase the distinction between inherent and non-inherent indicators of the selected source-to-service-to-sink (technology) chains should be made. The selected inherent indicators can serve as Environmental Business Performance Indicators (EBPI’s). In Figure 8 only small selections of possible environmental stressors are given in the inventory, though, as been mentioned before, LCA offers long lists of emissions and resource uses (Udo de Haes et al., 2002). By making a selection between inherent and non-inherent indicators the long lists are reduced to a more concise number of environmental stressors or environmental business pressures. The selection procedure of inherent and non-inherent indicators can be seen as the core of the industrial screening method and requires in depth knowledge of the selected source-to-service-to-sink (technology) chains. It is of high importance to include all inherent indicators. Overlooking inherent indicators of a specific chain might give a false prediction of the specific chain compared to the other chains involved in the optimization. Preferably, the selected inherent indicators should be:

- Relevant
- Measurable
- Concise
- Clear
- Acceptable
- Compatible
- Complete

The selected indicators should be relevant (inherent to the selected source-to-service-to-sink chains). They should be measurable, because the indicators will be used for optimization against other indicators (e.g. environmental and economic and social indicators). The indicators have to be concise and clear, because the optimization results have to be interpreted by people that will have to base business decisions on the optimization results. Besides, the selected indicators have to be acceptable within the concerning business(es) and have to be compatible with the (mathematical) optimization models that are used in the industrial optimization method. Furthermore the set of indicators has to be as complete as possible on the industrial screening level. The following step in LCA will help reduce the list of selected inherent indicators to a concise number of indices even more.

According to ISO (1997), the third phase, impact assessment, consists of 2 mandatory phases; classification and characterization (see Fig. 8). Classification is the assignment of inventory data to different impact categories (Udo de Haes et al., 2002). For example, greenhouse gas emissions are assigned to the impact category Climate Change’ (see Fig. 8) and Volatile Organic Compounds (VOC’s) to 'Photo-oxidant formation’. In the characterization phase environmental stressors assigned qualitatively to a particular impact category are quantified in terms of a common unit for that category, allowing aggregation into a single score; the indicator result (Guinée et al., 2002). Environmental stressors are quantified by so called characterization factors (or equivalency factors) multiplied by the quantity of the stressor resulting from the specific product or process.
Characterization factors express the contribution of each inventory item to a specific environmental problem (Udo de Haes et al., 2002). For example, in case of climate change, the equivalency factor of carbon dioxide is defined as 1, whereas the equivalency factor of methane is defined as 23, which means the radiative forcing (heat-absorbing ability) of methane is 23 times stronger relative to that of carbon dioxide (IPCC, 2001). When multiplied by the total quantities of greenhouse gas emissions of a production process the indicator result can be calculated. In case of climate change this can be expressed as total \( \text{CO}_2 \) equivalents (in kg), often described as Global Warming Potential (GWP). For most environmental problems equivalency factors to value impact potential are available. Examples other than GWP include Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP) and Human Toxicity Potential (HTP). Because the methodology of equivalency potentials aggregates different environmental pressures into one index, this step is very helpful in reducing the number of environmental indicators for industrial optimization into single indices. In the next paragraph the LCA impact categories and corresponding equivalency factors will be discussed.

Optional steps that belong to the midpoint level (the environmental mechanism, Fig. 8), but are not included in this study’s industrial screening and optimization methodology are normalization, grouping and weighting. Normalization is the calculation of the magnitude of the indicator result relative to well-defined reference information, for example kg CO\(_2\) equivalents in a reference area or compared to emissions in previous years. The normalization step can be implemented after the characterization step. The step can be included in the industrial optimization method, but is of help in the last phase (interpretation) of the optimization results. Grouping and weighting are both based on valuing the importance of the environmental stressors, impact categories or indicator results among each other, for example ranking or scaling the indicator results by monetary values or an expert panel (Guinée et al., 2002). Because this study’s industrial screening and optimization methodology should be as objective as possible it should be avoided to include (subjective) valuing in the optimization phase. This approach is comparable to classical LCA impact assessment methods (Jolliet et al., 2004) that stop quantitative modeling at the end of the midpoint level (Fig. 8). If needed, the optimization results can be given weights or grouped by (business) decision makers after the optimization phase. This approach is known as the damage oriented method (Jolliet et al., 2004), which is discussed below. Indicator methodologies as the Eco-indicator 99 and the Japanese Life-cycle Impact assessment Method (LIME) use this damage oriented method.

In the damage oriented method the indicator results are related to variables that are of direct societal concern, such as the human health, the natural environment or natural resources (Fig. 8). These are called damage categories or category endpoints (Udo de Haes et al., 1999). It would be desirable to draw quantitative impact pathways up to the damage categories, in which every single environmental stressor from the LCA inventory is linked to one or more specific damage categories. However, because of uncertain or lacking scientific agreement on the complex relationships between environmental mechanisms and the (actual) damage, it is not (yet) possible to include them in LCA (Udo
de Haes et al., 1999) and in the industrial screening and optimization method. The uncertain relationships between midpoint and endpoint categories are indicated by dashed arrows in Figure 8. An example of these uncertain relations can be given by biodiversity loss, which is a subcategory of the natural environment. Since there are many possible causes of biodiversity loss, it is almost impossible to define exactly which and how much impact certain environmental pressures have on biodiversity. For example, The Global Environmental Outlook 4 (UNEP, 2007) defines habitat destruction, invasive alien species, overexploitation, climate change and pollution as possible pressures to biodiversity loss (see also appendix 3).

Another example is the possible impact of Climate Change. In their fourth assessment report on climate change the IPCC (2007) has included different global scenarios for the change of temperatures in the future. Because of, for example, the uncertainties in radiative forcing it is not known which scenario will become reality and what the potential damage(s) will be to human health or the natural environment.

The fourth phase in LCA, **interpretation**, is to evaluate the LCA study in order to derive recommendations and conclusions (Udo de Haes et al., 2002). In case of industrial optimization and design the optimization results of the selected (inherent) indicators have to be interpreted. This can be done by, for example, running different scenarios and/or configurations of source-to-service-to-sink (technology) chains. It is also in this phase that weights can be assigned to environmental impact categories.

### 5.2 LCA impact categories and their relevance to industrial optimization

As been said LCA methodology makes use of impact categories and underlying stressor or pressure indicators, which can also be used for industrial screening and optimization. ISO 14042 (LCA) does not provide a default list of impact categories for inclusion in LCA. The text of ISO 14042 might be interpreted as indicating that these impact categories are to be defined anew for each LCA study (Guinée et al., 2002). However, most LCA studies include corresponding lists of impact categories. The impact categories and corresponding characterization factors that are used in this study are given in Table 2. These impact categories and their descriptions are taken from the Handbook on Life Cycle Assessment (Guinée et al., 2002). Corresponding characterization factors and examples are taken from both the Handbook on LCA and the IMPACT 2002+ User Guide (Humbert et al., 2005).
Table 2. Impact categories and corresponding characterization factor.

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Characterization</th>
<th>example</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depletion of abiotic resources</td>
<td>Abiotic Depletion Potential (ADP)</td>
<td>kg iron eq, kg oil eq</td>
<td>1</td>
</tr>
<tr>
<td>Depletion of biotic resources</td>
<td>Biotic Depletion factor (BDF)</td>
<td>n.a.</td>
<td>2</td>
</tr>
<tr>
<td>Land use</td>
<td>e.g. Land compaction</td>
<td>n/a</td>
<td>2</td>
</tr>
<tr>
<td>Freshwater withdrawal</td>
<td>Freshwater use</td>
<td>n/a</td>
<td>3</td>
</tr>
<tr>
<td>Climate change</td>
<td>Global Warming Potential (GWP)</td>
<td>kg CO2 eq</td>
<td>1,2</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>Ozone Depletion Potential (ODP)</td>
<td>kg OCF-11 eq</td>
<td>1,2</td>
</tr>
<tr>
<td>Acidification</td>
<td>Acidification Potential (AP)</td>
<td>kg SO2 eq</td>
<td>1,2</td>
</tr>
<tr>
<td>Photo-oxidant formation</td>
<td>Photochemical ozone creation potential (POCP)</td>
<td>kg ethylene eq</td>
<td>2</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>Eutrophication Potential (EP)</td>
<td>kg PO4 eq</td>
<td>1</td>
</tr>
<tr>
<td>Impacts of ionizing radiation</td>
<td>Ionizing Radiation Potential (IRP)</td>
<td>Bq carbon-14 eq</td>
<td>1</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>Human Toxicity Potential (HTP)</td>
<td>kg chloroethene eq</td>
<td>1</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>Ecotoxicity Potential (ETP)</td>
<td>kg hydroxybenzene eq</td>
<td>1</td>
</tr>
<tr>
<td>Noise pollution</td>
<td>Noise pollution</td>
<td>n/a</td>
<td>2</td>
</tr>
<tr>
<td>Colour</td>
<td>Colour Threshold Value (CTV)</td>
<td>n/a</td>
<td>2</td>
</tr>
<tr>
<td>Emission of hazardous substances</td>
<td>n/a</td>
<td>n/a</td>
<td>2</td>
</tr>
</tbody>
</table>

(Sources: 1: IMPACT 2002+ User Guide (Humbert et al., 2005); 2: Handbook on LCA, operational guide (Guinée et al., 2002); 3: addition of the author)

As can be derived from Table 2 the impact categories can be subdivided into input and output related categories. Input in this case means natural resources that are used by society (extractions and land use). Contrary to input related categories, output related categories are brought into the natural environment by man-made processes (emissions). Elements of society are production-consumption-related processes, such as industrial source-to-service-to-sink chains, which also use inputs from the natural environment, process these resources and finally emit substances into the environment. In the remainder of this paragraph the impact categories from Table 2 will be described briefly, including their relevance for the industrial screening and optimization method.

5.2.1 Depletion of abiotic resources

Abiotic resources are natural resources such as iron ore and crude oil that are regarded as non-living (Guinée et al., 2002). It is an umbrella impact category for several subcategories. The most common subcategories are metallic and non-metallic ores and minerals, fossil fuels and freshwater. In LCA abiotic resource use is seen as an environmental damage because the exploited resource generally leaves the system of anthropogenic processes in degraded form (Jolliet et al., 2004). Metallic and non-metallic ores and minerals and fossil fuels can be expressed as relative scarcity to other resources. Therefore, The Abiotic Depletion Potential (ADP) can be calculated based on the relative scarcity of ultimate reserves of ores and minerals and fossil fuels and their extraction rate (Guinée et al., 2002). In case of freshwater and soil, which are often included in the impact category of abiotic resource depletion, it is impossible to add them to the ADP in the same way as mineral and fossil resources, because their quality (and their relative scarcity as a result) is dependent on their geographical location. For example, freshwater in Norway is not the same as freshwater in the Sahel countries. In case of industrial screening and optimization, freshwater and soil are regarded as separate impact categories (impacts of freshwater use and impacts of land use). Although, in most LCA studies land use is included as a separate impact category, freshwater is included rarely. Furthermore, because resource scarcity in itself is not degrading the environment (according to the author resource scarcity is mainly a societal creation), the ADP should be included in industrial screening and optimization, however as an economic indicator instead of an environmental indicator. In the industrial screening and optimization
method environmental impacts (such as habitat loss) caused by extraction of resources (e.g. by mining) will be covered by the other impact categories, since for impacts from biodiversity and habitat loss there can be a variety of underlying environmental (business) pressures (e.g. UNEP, 2007; Spangenberg, 2007 and appendix 3). Therefore, on the project, plant and product level potential environmental impacts of resource depletion, such as habitat loss or loss of biodiversity, should be taken into account in for example an Environmental Impact Assessment (EIA) study. For example, by choosing between different potential mining locations, the mining location can be selected that has minimal impact on the (local) environment.

5.2.2 Depletion of biotic resources

Biotic resources are material resources regarded as living, e.g. rainforests and animals (Guinée et al., 2002). Identical to the impact category of 'abiotic resources' it is not possible to directly connect sub-impacts under biotic resource depletion (as biodiversity loss and habitat loss) to certain business processes on the industrial level (except for hunting and logging) because of the complexity of the ecological mechanisms (see also paragraph 5.1) and because their quality (and their relative scarcity) is dependent on their geographical location. Direct linkages of business processes are better identifiable on the project, plant and product level and taken into account on the local or regional level in for example an EIA study. For example, an oil pipeline that would split the habitat of a certain species can be constructed around the habitat to avoid disturbance.

However, in the industrial screening and optimization method indirect environmental pressures from biotic resource depletion will be covered by the other impact categories since for impacts as biodiversity and habitat loss their can be a variety of underlying environmental (business) pressures (e.g. land use, eutrophication). In this way, depletion of biotic resources can be left out of the industrial screening and optimization method.

5.2.3 Land use

The impact category 'land use' covers a range of consequences of human land use (appendix 3). The usage of land surfaces is, for example, recognized as a primordial threat to species and ecosystems (Jolliet et al., 2004). It is a relatively new topic in LCIA and is still being debated and developed (Guinée et al., 2002). Some LCA methods have subdivided land use in sub-categories as 'land occupation' (the unavailability of land for alternative use) and land transformation (the change in quality of land). This study will use 'land use change' as an umbrella proxy for several (endpoint) environmental impacts as biodiversity loss, habitat loss and soil degradation. Together with the other impact categories (like acidification and eutrophication) endpoint categories as biodiversity loss are covered indirectly in the industrial screening and optimization method. For example, waste disposal (in many sustainable production indicator frameworks covered as a separate category) can be split up into land use and the direct environmental impacts of the waste itself, such as acidification or eutrophication.

Land use can be expressed in square meters, in which an optional step in the inventory phase or interpretation phase is a valuing or weighting classification of different land use practices. As been said in the preceding paragraph, the weighting and valuing itself should not be included in the optimization phase itself because the optimization method
should be as objective as possible. Before or after the optimization phase weighting can be executed by business decision makers or can be enforced by external parties. Subsequently, as in the preceding impact categories, fine-tuning of land use related impacts can be executed on the project, plant or product level.

5.2.4 Freshwater withdrawal In LCIA (fresh)water is not included as a separate impact category, but as a subcategory of abiotic resource depletion. However, as stated in United Nations World Water Development Report 2 (UNESCO, 2007):

“Water is fundamental to our way of life, at whatever point in the socio-economic spectrum a community may be situated. It is likewise crucial to the preservation of the essential ecosystems upon which our lives depend”

As such, water is a unique resource and cannot be replaced by an alternative contrary to, for example, energy sources (WBCSD, 2006). Although freshwater is not considered a scarce resource globally, much of it is geographically inaccessible or not available throughout the year (WWF, 2006) and water resources are under increasing stress in many parts of the world (Owens, 2002). According to the UN World Water Development Report (UNESCO, 2007), “In many parts of the world, available water quantity is decreasing and quality is worsening, 1.1 billion people around the world lack access to improved water supplies and 2.6 billion lack access to improved sanitation”. It is not only water quantity that matters, as there are also main concerns that relate to the impacts of water pollution (water quality), such as eutrophication, acidification and toxic contamination, which can have impact on human health, on the cost of drinking water treatment and on aquatic ecosystems (OECD, 2007). In macro-system indicator frameworks (fresh)water quantity and quality are often addressed as important pillars of sustainable development (e.g. Eurostat 1999; OECD, 2007). (Fresh)water use is also included in most sustainable production indicator frameworks, e.g. in the Sustainability Metrics (IChemE, 2004); WBCSD Eco-efficiency indicators (Verfaillie and Bidwell 2000) and GRI Performance indicators (GRI, 2007). Because of the uniqueness of water resources and the increasing stresses on both water quantity and quality it is included as a separate impact category for industrial screening and optimization. Freshwater withdrawal, expressed in cubic meters, can be regarded as a proxy for water quantity whereas water quality is covered by impact categories as eutrophication, acidification and human and ecotoxicity. As in case of land use, a weighting classification of water use can be included. For example, different weights might be assigned to fossil water from aquifers compared to for example, recycled water. Weighting or valuing can be applied before or after the optimization phase. On the project, plant or product level fine-tuning of water related impacts can be executed, for example water quality indicators as Biochemical Oxygen Demand (BOD), pathogenic microorganisms and color and turbidity (see Owens, 2002). Because these indicators are dependent on local water conditions it is impossible to optimize them on the industrial system level: therefore these indicators cannot be included in the industrial screening and optimization method.
5.2.5 Climate change Climate Change refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2007). In recent years, climate change has gained a lot of interest among society, both in science, politics and in the media. Many companies have now acknowledged the relation of human-induced emissions and climate change, including companies like Shell. Climate change is the only category that is included in all macro-system and sustainable production indicator frameworks that are summed in Table 1. Moreover, climate change is included as an impact category in all LCA methodologies. Climate change characterization factors (equivalency potentials) of emissions are well known and science-based (e.g. IPCC, 2001; Guinée et al., 2002) and can be aggregated into a Global Warming Potential (GWP). In most cases GWP is expressed in CO₂ equivalents. In the industrial screening and optimization method single emissions factors or GWP can be used to quantify climate change.

5.2.6 Ozone depletion Stratospheric ozone depletion refers to the thinning of the ozone layer (reduction of ozone in the atmosphere) as a result of anthropogenic emissions (Guinée et al., 2002). The consequence is an increase of solar radiation, particularly UVB, on the earth’s surface, which in turn can cause, for example, skin cancer, harm to crops or harm to species and ecosystems (USEPA, 2000). In 1987 world leaders signed the Montreal Protocol, an international treaty designed to protect the ozone layer by phasing out the production a number of ozone depleting substances, e.g. CFC’s. Nonetheless, not all ozone depleting substances are phased out and are still emitted. Therefore, ozone depletion should be included in the industrial screening and optimization method, which can be accomplished by including single emissions factors or ODP as characterization method. From 1992 The World Meteorological Organization (WMO) has started to compile lists of Ozone Depletion Potential (ODP) of chemicals that can be used for this purpose (e.g. Guinée et al., 2002; WMO, 2007).

5.2.7 Acidification Through oxidation and hydrolysis, many substances can be transformed to acidifying substances. The resulting acids can be deposited as dust or dissolved in precipitation and in turn cause undesirable effects on terrestrial and aquatic ecosystems (decrease of pH, detrophication of soils) or damage to buildings (e.g. limestone can be dissolved by acid rain). As in case of climate change acidifying substances can be aggregated to an Acidification Potential (AP) which can be used for industrial optimization. AP can be expressed in SO₂ equivalents, which is based on the Redfield Ratio (first described in: Redfield, 1934).

5.2.8 Photo-oxidant formation Photo-oxidant formation is the formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants. These reactive compounds may be injurious to human health and ecosystems and may also damage crops (Guinée et al., 2002). Unlike greenhouse gases that act in the atmosphere, photo-oxidants form in the troposphere (a lower altitude) under the influence of UV light and through photochemical oxidation of Volatile Organic Compounds (VOC’s) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) (Guinée et al., 2002). Ozone is considered the most important of these oxidizing compounds, though should not be confused with ozone depletion since ozone depletion acts on a higher
altitude in the atmosphere. Photo-oxidant formation is also known as summer smog and contrast winter smog. Winter smog is caused by inorganic compounds, mainly particulates (PM), carbon monoxide and sulphur compounds and can cause, for example, bronchial irritation. However, winter smog is included in LCA under the impact category Human Toxicity. Photo-oxidant forming substances can be aggregated in a Photochemical Ozone Creation potential (POCP), which can be expressed in ethylene equivalents (Guinée et al., 2002; Humbert et al., 2005).

5.2.9 Eutrophication  Eutrophication covers all potential impacts of excessively high environmental levels of nutrients, of which nitrogen (N) and phosphorus (P) are the most important ones. Eutrophication can be expressed in PO$_4^{3-}$ (Humbert et al., 2005) and can be subdivided in aquatic and terrestrial eutrophication. In case of industrial screening and optimization this distinction is not made, because a useful distinction can only be made when it is known whether nutrients deposit on water or on land. Therefore this subdivision should be included in optimization on the project, plant or product level.

5.2.10 Impacts of ionizing radiation  Impacts of ionizing radiation, which are not always included in LCA impact categories, cover the impacts arising from releases of radioactive substances. They can be expressed as Ionizing Radiation Potential (IRP) for use in LCA or industrial screening and optimization.

5.2.11 Human toxicity  Covers the impacts of toxic substances on humans (Guinée et al., 2002). There is a wide range of possible effects from toxic substances and there is an even larger list of toxic chemicals that could affect human health and few have been subjected to toxicological evaluation (studies about their potential effects). These factors make an assessment of human toxicity difficult at best (USEPA, 2000). It is possible to aggregate substances on their toxicity potential, but as been said before, not all toxic chemicals have been evaluated on their toxicity. Therefore, on the source-to-service-to-sink chain screening and optimization level (inherent) toxic chemicals can be included separately (such as particulate matter), although for most substances it will be more useful to include human toxicity on the project, plant or product level, since exposure rates of receiving bodies can only be determined on this level.

5.2.12 Ecotoxicity.  Covers the impacts of toxic substances on ecosystems (e.g. Guinée et al., 2002). For this impact category a variety of different characterization methods is available that depend on the type of ecosystem that is affected. Guinée et al. (2002), for example, make a distinction in freshwater and marine aquatic ecotoxicity and terrestrial ecotoxicity. Hence, it is necessary to know in which ecosystems type (receiving bodies) toxic chemicals end up. This can only be determined on the project, plant or product level (local or regional level). However, it is possible to include single (inherent) chemicals of source-to-service-to-sink chains in the industrial screening and optimization method.
5.2.13 Waste heat  Emissions of waste heat such as cooling water may increase temperatures on a local scale. Waste heat might result in temperature rise of water bodies which in turn can have impact on local aquatic ecosystems. Although waste heat can be inherent to some technology chains, actual impact waste heat can be determined on the project, plant or product level, because the temperature of the receiving body must be known. Because of this waste heat is more suitable in for example an EIA study.

5.2.14 Odour  Becomes a problem when a given concentration of odorous substances is experienced as unpleasant (Guinée et al., 2002). Since this is dependent on the perception of the receiving body this impact category should be included on the local level, either the project, plant or product level.

5.2.15 Noise  Refers to the environmental impacts of sound and is similar to odour in that it is dependent on the perception of the receiving body. Therefore noise should also be included in optimization on the local level.

5.3 Conclusion

It can be concluded in principle all LCA impact categories that in principle all impact categories (see Table 2) can be used in industrial screening and optimization. However, because the actual environmental impacts of depletion of both biotic and abiotic resources are covered by the other categories, depletion of biotic and abiotic resources can be included in the method as semi environmental impact categories.

Furthermore, some impact categories are more suitable on the project, plant or product level, because the actual impact is dependent on the conditions of the local environment or actual exposure to receiving bodies (toxicity, odour, noise and waste heat). Because on the industrial level this relation to actual exposure or impact is often uncertain and in some cases unknown, the impact categories human toxicity, ecotoxicity, waste heat, odour and noise can be seen as optional. Of these categories odour and noise can have local impact exclusively while human and ecotoxicity and waste heat can have impact on a larger scale, because these impacts can be ’carried’ by a medium such as a river (waste heat) or by the atmosphere (toxic chemicals). Inclusion of a business pressure into the industrial screening and optimization method that falls into an optional impact category should be inherent to the specific source-to-service-to-sink technology chain and requires a clear (science-based) relation between the specific business pressure and the actual impact it causes. An example is particulate matter (or fine particles) such as PM$_{10}$ or PM$_{2.5}$ in which the digits stand for the size of the particles (in micrometers). Fine particles have known impacts on human and animal health and can, for example, cause respiratory and carcinogenic diseases (e.g. Englert, 2004). Fine particles are emitted by the combustion of fossil fuels (e.g. coal, diesel).

Impact categories that should be included in every industrial screening and optimization study, because of there potential large scale effects (regional or global), are land use, freshwater withdrawal, climate change, ozone depletion, acidification, photo-oxidant formation, eutrophication and impacts of ionizing radiation. These categories can be
regarded as standard categories, though not all of these categories have to be inherent to the specified source-to-service-to-sink technology chains that are selected in an optimization study. One could argue that also land and freshwater use, photo-oxidant formation and eutrophication impact on a local level. However, one should also acknowledge that these local impacts are taking place on a large scale and have similar effects all around the globe. In this thesis these impacts will be referred to as glocal environmental impacts and are defined as local impacts that take place on a global scale. Although the term is deducted from it, the definition of "glocal" is not to confuse with the (in the 1980’s developed Japanese business) term globalization, which refers refers to the individual, group, division, unit, organization, and community which is willing and is able to: “think globally and act locally.”

Both standard and optional categories are depicted in Table 3, which also includes equivalency factors that might be used for aggregation of business pressures into one single index.

Table 3. Proposed impact categories for industrial screening and optimization, including corresponding equivalency factors and examples of business pressures.

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Equivalency Factor*</th>
<th>Examples of Business Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use</td>
<td>m^2/yr</td>
<td>Land use change</td>
</tr>
<tr>
<td>Freshwater withdrawal</td>
<td>m^3/yr</td>
<td>Freshwater use</td>
</tr>
<tr>
<td>Climate change</td>
<td>Kg CO2 eq.</td>
<td>Greenhouse gases</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>Kg CFC-11 eq.</td>
<td>Halocarbons (CFC’s)</td>
</tr>
<tr>
<td>Acidification</td>
<td>Kg SO2 eq.</td>
<td>E.g. sulphur oxides, nitrogen oxides, ammonia</td>
</tr>
<tr>
<td>Photo-oxidant formation</td>
<td>Kg ethylene eq.</td>
<td>E.g. VOC’s, nitrogen oxides (NOx)</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>Kg PO4^3 eq.</td>
<td>Nitrogen, phosphorus (and in water: COD)</td>
</tr>
<tr>
<td>Impacts of Ionizing radiation</td>
<td>Bq carbon-14 eq.</td>
<td>Radioactive minerals</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>Kg chloroethylene eq.</td>
<td>Toxic substances</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>Kg triethylene glycol eq.</td>
<td>Toxic substances</td>
</tr>
<tr>
<td>Waste heat</td>
<td>(factor is 1 for all stressors)</td>
<td>E.g. cooling water</td>
</tr>
<tr>
<td>Local impacts (plant, project, product level)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odoer</td>
<td>Chlorobenzene eq.</td>
<td>Odour emissions</td>
</tr>
<tr>
<td>Noise</td>
<td>N.a.</td>
<td>Noise emissions</td>
</tr>
<tr>
<td>Optional categories</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depletion of Abiotic resources</td>
<td>Kg iron eq., Kg oil eq.</td>
<td>Extraction/ mining</td>
</tr>
<tr>
<td>Depletion of Biotic resources</td>
<td>N.a.</td>
<td>E.g. logging, hunting</td>
</tr>
</tbody>
</table>

* Can be used as indices for industrial optimization and design
** "Actual impacts" are covered by the standard impact categories
*** Economic impact (scarcity)
6. The industrial screening and optimization method

As has been described in chapter 5 ISO has established a fixed LCA protocol (ISO 14040), which contains 4 phases. Because the here proposed industrial screening and optimization method uses, in part, the same methodology as LCA, the ISO protocol (ISO, 1997) is also useful as guideline for an industrial screening and optimization study. An industrial screening and optimization study needs to be carried out or accompanied by experts on the included technology chains as well as experts on the environmental impacts of the specific technology chains. Because entire source-to-service-to-sink chains are seldomly ‘possessed’ by a single company, cooperation between companies might also be required.

The here proposed industrial screening and optimization method includes the following phases:

**Goal and scope definition.** In the first phase, the source-to-service-to-sink chains, which will be optimized against each other, need to be selected and described. Selection should be based on a certain societal need or in LCA terms on the functional unit. As defined by Guinée et al. (2002) a *functional unit* is the quantified function provided by the product (in this case the selected technology chains) under study. This can, for example, be the need for mobility (functional unit: passenger kilometers) or the need for light (functional unit: hours of light). Boundary setting of the technology chain should also be included in this phase. The boundary setting, the building blocks that will be included, should be equal for each technology chain, if chains are optimized against each other (see Fig. 9).

![Boundary Setting Diagram](image)

*Figure 9. Example of boundary setting (dotted box) within the industrial screening and optimization method.*

Furthermore, this phase should include a description of current best-practice technologies (as described in Box 1) of the selected chains. Improved technologies of the specific technology chain that can become best practice in the future, but are either not (yet) economically viable or have not been introduced because of other reasons can also be included in this phase.
Inventory analysis. The second phase consists of data collection on environmental stressors (environmental pressures) that are connected to selected source-to-service-to-sink technology chains. Input related (land use and freshwater withdrawal) as well as output related pressures (emissions) of the technology chains should be included in the inventory. Furthermore, a distinction between inherent and non-inherent pressures (Box 1) of the selected source-to-service-to-sink (best practice technology) chains should be made. The business pressures should be (see also paragraph 5.1):

- Relevant
- Measurable
- Concise
- Clear
- Acceptable
- Compatible
- Complete

Since the impact assessment phase and the inventory phase are mutually dependent they can be accomplished in combination.

Impact assessment. The resulting business pressures from the inventory can be classified according to the impact categories mentioned in Table 3. For each impact category the underlying business pressures can be characterized and, if possible, aggregated through characterization or equivalency factors. The result of this phase should be a concise set of indices, if necessary appended by single indicators that can be used for optimization. As the impact assessment phase and the inventory phase are mutual dependent they can be combined.

Optimization. The indices from the impact assessment phase can be used in an optimization model together with financial and social indicators. In the model multiple (energy) technology chains are optimized against each other with the help of computer models/programs. A distinction can be made between optimization within or between the selected source-to-service-to-sink technology chains. Inherent environmental indicators can be used as EBPI’s for industrial optimization and industrial design (between and of multiple source-to-service-to-sink chains). Both inherent and non-inherent indicators can be used for optimization within a single source-to-service-to-sink chain (see also paragraph 4.2 and Box 1.) It is possible to add indices other than environmental, such as social or economic indicators to the optimization model. The results of the optimization phase can, for example, be presented in spider diagrams (appendix 4).

Interpretation. In the last phase the results of the optimization phase have to be analyzed and interpreted by experts and can be used for business decision making. This can for example be done by running different scenarios and/or configurations of source-to-service-to-sink (technology) chains. It should also be possible to identify the position within technology chains that relatively cause the most environmental impact, which can for example be subjected to a lower level LCA (on the product or process level).
7. Oil sands technology chains and their environmental impacts

7.1 Introduction

The here proposed industrial screening and optimization method has been tested on its practicability by including a case study on oil sands technology chains and its environmental impacts. In an industrial screening and optimization study oil sands technology can be screened on inherent and non-inherent environmental impacts. Consequently, oil sands technologies can be optimized within the oil sands source-to-service-to-sink chain itself (inter-optimization) or against other energy systems (intra-optimization) such as conventional oil technology chains or renewable technology chains of solar, wind and hydro power (Fig. 10).

Oil sands, also known as tar sands, are naturally occurring viscous mixtures of sand or clay, water and heavy oil (crude bitumen). The crude bitumen will not flow to a well in its natural state (Woynillowicz et al., 2004). Oil sands are classified as unconventionals, which means it is using techniques other than the traditional oil well method. The main world reserves of oil sands are located in Alberta, Canada. It is estimated that 1.7 trillion barrels of crude bitumen are available in Alberta and that 180 billion barrels could be economically recovered using currently available techniques (Alberta Energy and utilities Board, 2004). These reserves are second only to Saudi Arabia in quantity and represent about 15% of global oil reserves (Bergerson and Keith, 2004). Although it is more
problematic to extract oil from oil sands compared to conventional oil extraction, oil production from oil sands is increasing rapidly (Bergerson and Keith, 2004).

Because of the lack of (scientific) studies on entire source-to-service-to-sink energy chains and their environmental impacts, LCA and environmental impact studies of single building blocks of the oil sands source-to-service-to-sink chain have been combined in this study. Probably because of the recent public attention to oil sands, there are some recent studies that have focused on environmental impacts of oil sands technology. The availability of environmental reports about oil sands is one of the reasons why oil sands are chosen to serve as a case study for industrial screening and optimization.

The intention of this case study is only to clarify the proposed industrial screening and optimization method by a practical example. It is by no means intended to quantify the environmental impacts of oil sands technology and the only sources that are used in the case study are taken from literature. Although these sources will give a good overview on the environmental impacts of oil sands, more detailed studies and contributions of environmental and oil sands technology experts are required when oil sands technology pathways are to be included in an energy optimization model such as depicted in Figure 10.

The case study on screening and optimization of oil sands technology pathways and their environmental impacts will be performed based on the 5 phases of industrial screening and optimization (paragraph 5.3) and will be described in the following paragraphs.

7.2 Goal and scope definition

This phase should include a definition of the functional unit, the selection and boundary setting of the source-to-service-to-sink technology chains and descriptions of the selected chains.

The functional unit can be determined by the quantified function that is provided by the product. The goal of this optimization would be to compare different fuel pathways on their impact, in which oil sands is one of these pathways. In this case mobility is taken as the function of the product system (fuels) and can be expressed in, for example, passenger-kilometers. If other fuel pathways will be added for optimization the functional unit should be the same. The boundary setting of the oil sands pathway is comparable to well-to-wheel analysis and includes the environmental impacts from the extraction of raw materials (mining and drilling) to manufacturing (upgrading and refining) to end-use of (fuel use). Since there are no studies of environmental impacts of entire well-to-wheel oil sands pathways, the environmental impacts have been 'collected from' different sources. The oil sands extraction technologies and their environmental impacts are mainly taken from the Oil Sands Technology Roadmap from the Alberta Chamber of Resources (2004) and an environmental impact study of the Pembina Institute (Woynillowicz et al., 2005). For the refining and combustion (final fuel use) building blocks of the source-to-service-to-chain The World Bank Health and Safety Guidelines for Petroleum Refining (The
World Bank, 2007) and a Life Cycle Analysis of (conventional) oil of the Harvard Medical School (Epstein et al., 2002) have also been used.

7.2.1 Technology pathway description

For bitumen extraction from oil sands two different types of technology are currently in use; surface mining and in-situ extraction. For surface mining the deposit must be less than 100 meters from the surface (Woynillowicz et al., 2005). To access deeper deposits in situ recovery is used. The Alberta government has estimated that approximately 93% of Alberta’s oil sands can only be developed using in situ recovery (Woynillowicz et al., 2005). The majority of Alberta’s oil sands production currently comes from oil sands mining, but in situ production will become the dominant extraction method in the coming decades (Woynillowicz et al., 2005). In Figure 11 a schematic overview is given of the oil sands surface mining technique. In the first phase the area is deforested and cleared of soil, after which the oil sand is mined and loaded onto trucks. The oil sands are then crushed to remove rocks and are mixed with water to create a slurry mix. The slurry is pumped into a separation vessel in which the sand settles to the bottom and the bitumen raise to the top (froth). This froth is then skimmed off and mixed with a solvent in a centrifuge to remove water and clay. The bitumen can then be processed into crude oil.

Figure 11. Oil sands surface mining process (Source: The Washington Post, 2005).

There are various in situ techniques to extract oil from oil sands however High Pressure Steam Assisted Gravity Drainage (SAGD) is the business’ best practice technology (Halog and Chan, 2006). A schematic overview of SAGD is given in Figure 12.

Figure 12. SAGD oil sands extraction technology (Source: The Washington Post, 2005).

SAGD technology is similar to conventional oil drilling techniques. Oil wells are drilled into the ground after which steam is injected under high pressure into the top well head
(Fig. 12). The perforations in the well allow the steam to enter the oil sands deposit. Heat loosens and softens the bitumen and water vapor dilutes and separates it from the sand and can be collected in the bottom well. Bitumen is then pumped up to the surface by the bottom well and can be processed further.

Bitumen is deficient in hydrogen compared with typical crude oils, which is why it first has to be upgraded or transformed into synthetic crude oil before it can be refined. Upgrading bitumen utilizes natural gas as a source of heat and steam for processing, and also as a source of hydrogen for hydroprocessing. Upgrading mainly requires two stages. The first stage cracks the large bitumen hydrocarbons into smaller molecules, which can be done by either coking (removal of excess carbon), hydrocracking (addition of hydrogen) or both. In a second stage nitrogen and sulphur are removed through heating. The nitrogen is removed as ammonia while the sulphur by-product is converted to elemental sulphur (Woynillowicz et al., 2005). For a more detailed picture of upgrading see appendix 5.

After upgrading the oil can be transported to a refinery where complex hydrocarbon compounds are separated, converted and treated to become useable fuel sources such as gasoline, diesel, kerosene, lubricating oils and asphalt. Separation involves the division of crude mixtures by boiling or vaporizing the crude oil into fractionating towers. The next stage, conversion, alters the less valuable fractions into more valuable products by cracking (breaking up longer molecule chains into smaller ones). Finally, impurities are removed through chemical treatment (Epstein et al., 2002). In this case study the end products are fuel products, for example gasoline and diesel, which are used in a combustion engine. For simplicity reasons the environmental impacts of this case study are limited to general impacts of combustion of fossil fuels as is done in the LCA of oil by Epstein et al. (2002).

7.3 Inventory analysis

As can be derived from Figure 13 the environmental pressures of the oil sands source-to-service-to-sink technology chain are pressures from extraction (surface mining and in situ extraction), upgrading, refining and end-use (combustion). Impacts from transportation and distribution ‘between the different building blocks’ of the well-to-wheel oil sands pathway are relatively small and therefore not included. The environmental pressures of the individual buildings blocks will be described in the following subparagraphs.
Figure 13. Environmental pressures of oil sands source-to-service-to-sink chains.

7.3.1 Oil sands extraction

The main environmental pressures from the extraction of oil sands are land and freshwater use. In case of surface mining land is cleared from vegetation and topsoil, rivers are diverted and wetland complexes are drained (Woynillowicz et al., 2005). The future reclaimed landscape proposed by the oil sands industry will be radically different and will lead to dry forested hills instead of wetlands, a larger percentage of lakes and the absence of peatlands (Woynillowicz et al., 2005). In situ extraction (SAGD) requires no excavation and less surface area but is associated with fragmentation of the forest from the construction of roads, seismic lines and exploration well sites (National Energy Board, 2006).

Both mining and in situ operations use large volumes of water for extracting bitumen from the oil sands. Between 2 to 5 barrels of water are withdrawn primarily from the Athabasca River, to produce a barrel of synthetic crude oil (Woynillowicz et al., 2005). In case of surface mining, despite recycling, almost all of the water withdrawn for oil sands operations ends up in so-called tailing ponds. Tailing ponds are artificial lakes that consist of a slurry of bitumen, water, sand, silt and fine clay particles. In these ponds, the sand, silt and fine clays slowly settle to the bottom. Then, as much water as possible is pumped back to the extraction plant and reused in the extraction process (Woynillowicz et al., 2005). Approximately six cubic meters of tailings are created for every cubic meter
of bitumen produced. The tailings are comprised of 3-5 cubic meters of water and approximately 1.5 cubic meters of fluid fine tailings (Alberta Chamber of Resources, 2004). In 2005 tailings already covered an area of land greater than 50 square kilometers (Woynillowicz et al., 2005), while oil sands mining is only at its beginning. The tailing ponds also pose a number of other environmental risks like pollution of groundwater from naphthenic acids and air pollution of VOC’s like benzene.

Another environmental concern from surface mining is the mine fleet of trucks and shovels. A truck can have an engine that is roughly equivalent in size to a locomotive engine (Woynillowicz et al., 2005). Since the mine fleet mainly uses diesel as a fuel the emissions are related to diesel engine emissions such as CO$_2$, CO, SO$_x$ (SO$_2$), VOC’s, NO$_x$, and particulates.

In case of SAGD technology the oil is separated underground from the sand and can be pumped to the surface afterwards, which makes that there are no impacts from tailings ponds or a mining fleet. However, in situ techniques need more natural gas to generate the steam to extract the oil. About 1000 cubic feet of natural gas are needed to extract one barrel of bitumen, which is enough to heat a Canadian home for 5.5 days (Woynillowicz et al., 2005). Furthermore, SAGD projects minimize the use of freshwater aquifers by using freshwater mixed with saline groundwater. However, treating saline groundwater for the steam generators produces large volumes of solid waste. The disposal of this waste to landfills is another long-term concern because it could impact nearby soil and groundwater. It contains high concentrations of acids, hydrocarbon residues, trace metals and other contaminants (Alberta Chamber of Resources, 2004).

In fact, all environmental pressures mentioned and depicted in Figure 13 that are related to mining (surface and SAGD) can be regarded as inherent environmental indicators to oil sands operations and can therefore be incorporated in the screening and optimization method. Though, the impacts from the solid waste from treating saline groundwater should be investigated further on its compatibility with (whether it is inherent to) the oil sands operations (if they can be prevented by best practice technology within the chain.)

**7.3.2 Upgrading**

The main environmental pressures from oil sands upgrading technology are related to the use of natural gas, which is needed for hydrogen production, freshwater use for and emissions from upgrading processes. Emissions from upgrading plants are Nitrogen (removed as ammonia), SO$_2$, although most of the sulphur can be converted to elemental sulphur, and CO$_2$ (Woynillowicz et al., 2005). As in case of oil sands extraction environmental indicators can be regarded as inherent to the oil sands upgrading process technology. However, because the environmental pressures (especially emissions) from upgrading are not described in detail in the reports that are used in this case study, a more in depth analysis of impacts might be required of, for example, an upgrading plant, in order to incorporate into an optimization model.
7.3.3 Refining

Oil refining can have numerous environmental pressures. Although most gases in the refinery can be recaptured with complex scrubbers or filters to avoid atmospheric contamination, complete elimination of the emissions is impossible with existing best practice technologies (Epstein et al., 2002). Emission that are mentioned in The World Bank Health and Safety Guidelines for Petroleum Refining are CO, NO\textsubscript{x}, CO\textsubscript{2} and SO\textsubscript{x}, CH\textsubscript{4}, VOC’s (e.g. ethane, ethylene, propane and benzene) Polycyclic Aromatic Hydrocarbons (PAHs) and particulates (The World Bank, 2007). Furthermore, oil refineries use large volumes of water, especially for cooling systems (The World Bank, 2007). Process water may be contaminated with hydrocarbons (VOC’s), hydrogen sulphide, ammonia, organic sulphur compounds, organic acids and phenol. Although most waste water is recycled and/or treated to remove contaminants, accidental discharges of pollutants can occur as a result of abnormal operation (The World Bank, 2007). Other environmental pressures that mainly can affect (local) human health (oil refinery workers or the local population) are noise (The World Bank, 2007), odour and hazardous (toxic) materials, including asphalt, arsenic, nickel, coke dust, lead alkyls and silica (Epstein et al., 2002).

Both waste water and toxic materials from refineries are regarded as non-inherent to the oil sands source-to-service-to-sink chain, because they are related to spills that can be prevented (in theory) by best practice technology (e.g. by process control). Moreover, especially in case of toxic materials impacts are dependent on local circumstances (receiving bodies). Therefore, it is more effective to handle spills and related environmental pressures on the plant, project or product level.

Because oil refineries are complex sites and are never identical quantification of the different environmental pressures might be problematic. However, it is possible to calculate average emissions from refineries as described by The World Bank (1999) in their 1998 Pollution Prevention and Abatement Handbook. For example, for each ton of crude processed they have estimated that 0.8 kg of PM, 1.3 kg of SO\textsubscript{x} (with the Claus sulphur process), 0.3 kg NO\textsubscript{x}, and 1 kg VOC (depends on technique and climate conditions) is emitted (The World Bank, 1999).

7.3.4 End-use

As been said in the preceding paragraph, the environmental pressures from the end-use (consumption of fuel for mobility purposes) are limited to the general pressures from the combustion of fossil fuels and can be brought back to 7 air pollutants that can have effect on society (human health) and ecosystems. As mentioned by Epstein et al. (2002) these are CO\textsubscript{2}, CO, SO\textsubscript{x} (SO\textsubscript{2}), VOC’s, NO\textsubscript{x} and Particulate Matter (PM2.5 and PM10) and lead. Although the addition of lead to gasoline is banned in several countries, because of impacts on human health, lead emissions from combustion of gasoline in the developing world are still common (O’Rourke and Connolly, 2003). In this case, environmental pressures from end-use that are mentioned in this paragraph, can be regarded as inherent, although some of these can be regulated to some extent by refined techniques for
combustion engines, such as exhaust filter (soot) or catalysts. These techniques can be included in the optimization model as different configurations.

7.4 Impact Assessment

Here, the resulting business pressures from the inventory can be classified and aggregated by impact category through characterization factors. In Table 4 the business pressures from the oil sands technology chain (Fig. 13) have been grouped by their environmental impact category. Subsequently, the individual pressures can be aggregated by their impact potential into an impact index. These impact indices (equivalency potential) can be used in the optimization model.

Table 4. Oil sands pressures classified by impact category, including possible impact indices (pressures in grey can be regarded as non-inherent).

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Environmental pressures from Oil sands</th>
<th>Impact index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use</td>
<td>land use change</td>
<td>m²</td>
</tr>
<tr>
<td>Freshwater use</td>
<td>freshwater use</td>
<td>m³</td>
</tr>
<tr>
<td>Climate change</td>
<td>CO₂, CH₄</td>
<td>CO₂ eq.</td>
</tr>
<tr>
<td>Acidification</td>
<td>SO₂, NOₓ, ammonia</td>
<td>SO₂ eq.</td>
</tr>
<tr>
<td>Photo-oxidant formation</td>
<td>CO, SO₂, VOC’s (e.g. benzene), NOₓ, CH₄</td>
<td>ethylene eq.</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>NOₓ, ammonia</td>
<td>PO₄ eq.</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>VOC’s (e.g. benzene), toxic materials (e.g. nickel, coke dust, lead alkyls, silica), PM, SOₓ, PAH’s</td>
<td>chloroethylene eq.</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>VOC’s (e.g. benzene), toxic materials (e.g. nickel, coke dust, lead alkyls, silica), PM, SOₓ, PAH’s</td>
<td>triethylene glycol eq.</td>
</tr>
</tbody>
</table>

The pressures from oil sands source-to-service-to-sink technology chains that are mentioned in Figure 13 and in Table 4 can all be regarded as inherent to the studied (best practice) oil sands technology chain, except for the pressures that are related to spills or accidents. Since these pressures can be prevented (in practice) by the concerned best practice technology these cannot be considered as inherent indicators (see Box 1). Most of these pressures (toxic materials) are related to the impact categories human toxicity and ecotoxicity, which are already regarded as optional categories in the industrial screening and optimization method since exposure to receiving bodies (humans or animals) can only be determined on the local level. Exceptions to this rule might be the emission of PM and SOₓ, which are related to the combustion of fossil fuels. As in case of acidification, photo-oxidant formation and eutrophication their impact is local. However, these local impacts are taking place on a large scale and have similar effects all around the globe. These impacts can therefore be acknowledged as glocal environmental impacts (see also paragraph 5.3).

The aggregation of single indicator into indices results in a select number of indices that can serve as environmental business performance indicators for industrial optimization and design for oil sands technology chains, namely the 8 impact indices that are mentioned in Table 4. Non-inherent indicators and their impact (as toxic materials and...
PAH’s from spills and accidents, but also noise, odour and waste heat) can be fine-tuned on the plant, project or product level in for example an EIA. In case of land and freshwater use, characterization factors (equivalency factors) of different types of land or freshwater use might be used (e.g. fossil freshwater versus recycled water). Since these characterization factors are not available in LCA further research will be required in this field.

7.5 Optimization and interpretation

For the oil sands source-to-service-to-sink chain the 8 impact indices of Table 4 can be used in a mathematical optimization model for energy system (intra) optimization (as in Fig. 10). When studies of other energy systems and their inherent environmental pressures will be included as well it is possible to optimize not only on financial indicators but also on (potential) environmental impacts. For example, spider diagrams that include both financial indicators and environmental indices can be used for scenario development and prognosis models which can serve as a basis for business decision making and industrial design. When, besides financial and environmental indicators, social indicators will be included in the optimization model it will be possible to optimize on the three pillars of sustainability: People, Planet and Profit. In this case, the method can be denominated as (industrial) “triple bottom line optimization”.
8. Conclusions

This chapter summarizes the conclusions of this master degree thesis and answers the following research question formulated in Chapter 1:

Which environmental indicators are applicable as business performance indicators and how can they be applied in an industrial optimization model for industrial design?

To answer the research question this study was split up into three parts; an inventory and analysis of existing environmental indicator frameworks (1); selection and translation of indicators to an industrial optimization method (2) and finally (3) the application of the selected indicators and methodology to a practical case (the oil sands industry). The three parts together provide the answer to the research question. The conclusions of each part are described in the next three paragraphs (8.1-8.3).

8.1 Conclusions from the inventory and analysis of environmental indicator frameworks

From the inventory and analysis of the environmental indicator frameworks can be concluded that frameworks can be categorized by their level of analysis. Indicator frameworks are distinguished between macro, meso and micro-level frameworks. However, as far is known to the author, none of these frameworks have used or developed environmental indicators for industrial optimization and design. Macro-system frameworks give good insight in the (global, regional or national) state of the environment, but do not describe environmental problems and environmental indicators and their relation to business in detail or in such a way that it is possible to directly use them as environmental business performance indicators. Meso-level frameworks focus on the industrial system or on the company level. Although this is on the level of industrial optimization, the indicator frameworks mainly focus on dematerialization of business processes (production) instead of decreasing environmental impact directly through adaptive innovation. Dematerialization in itself does not necessarily decrease environmental impacts and can even have adverse effects or lead to environmental impact trade-offs. The most effective way to decrease environmental impact from businesses is to decrease environmental business pressures through adaptive innovation. Micro-system frameworks are focused on the project, plant and product level and include direct linkages between these environmental pressures and businesses (e.g. LCA, EIA). However, contrary to the macro-system indicator frameworks, micro-system frameworks are too detailed to use their entire set of indicators as performance indicators for industrial optimization and design. Therefore, this thesis has developed an industrial screening method that distinguishes between inherent and non-inherent environmental pressure indicators of businesses and that makes use of ISO based Life Cycle Analysis methodology.
8.2 The industrial screening and optimization method

Inherent indicators measure environmental pressures that are characteristic of a source-to-service-to-sink chain and that cannot be prevented by best practice technologies of the specific chain. In the industrial screening and optimization method source-to-service-to-sink chains are screened on inherent indicators, which can then serve as inputs to industrial optimization models that compare different source-to-service-to-sink chains. Non-inherent environmental indicators are also characteristic of a specific source-to-service-to-sink chain, but can be prevented by best practice technology of the specific chain. They can be optimized (minimized) within a single technology chain. It is not useful to compare technology chains on their non-inherent indicators since they can be minimized within the single chains.

Environmental business pressures, which can be divided into inherent and non-inherent indicators, can be structured by LCA impact categories. These impact categories arrange single business pressures into one impact by scientifically based aggregation methods. This results in a concise number of impact indices that can be used in an industrial optimization model. Basically, all LCA impact categories include business pressures that can be inherent to the selected source-to-service-to-sink chains. However, this thesis makes a distinction between standard and optional impact categories. The distinction is based on the scale of impact instigated by underlying business pressures. For example, climate change will impact the entire globe, while a toxic substance might ’only’ affect local populations or ecosystems. The latter impacts can be considered (specifically on prevention and reduction potential) by other environmental assessment methods like EIA. Provided that underlying indicators are inherent to the specific technology chain, standard impact categories that should always be included in industrial optimization are land use, freshwater withdrawal, climate change, ozone depletion, acidification, photo-oxidant formation, eutrophication and ionizing radiation. These impact categories are of global or glocal nature. "Glocal" impacts in this case are local impacts that take place on a global scale, such as land and freshwater use, photo-oxidant formation or eutrophication. Environmental business pressures that impact on the local scale and therefore can be regarded as optional in the environmental optimization method, are human and ecotoxicity, waste heat, odour and noise. Exceptions to this rule can be made for, for example, particulate matter, which is an environmental business pressure that falls into the impact category human toxicity. Particulate matter is a perfect example of a business pressure with a glocal impact and should therefore be included (if inherent) as an indicator in the screening and optimization method.

In LCA depletion of both biotic and abiotic resources are also included, but are not regarded as environmental impacts in the industrial optimization method. Resource scarcity is regarded as an economic impact, environmental impacts from resource extraction are covered by the other environmental impacts which are already included as standard impact categories (e.g. land use).
The phases used in the ISO LCA protocol (ISO 14040) can also be used as a backbone for the industrial screening and optimization method. In short these phases are:

1. **Goal and scope definition**: Source-to-service-to-sink technology chains, which will be optimized against each other, are selected and described. The selection should be based on a predefined functional unit. This phase should also include the boundary setting of the segments of the source-to-service-to-sink technology chains.

2. **Inventory analysis**: Consists of data collection on the environmental pressures from the selected source-to-service-to-sink technology chains, in which a distinction should be made in inherent and non-inherent environmental pressures.

3. **Impact assessment**: The resulting (inherent) business pressures from the inventory can be categorized and aggregated by impact categories into impact indices.

4. **Optimization**: The indices from the impact assessment phase can be used in an optimization model together with financial and social indicators. In the model multiple (energy) technology chains are optimized against each other.

5. **Interpretation**: Results of the optimization phase have to be analyzed and interpreted by experts and can be used for business decision making.

### 8.3 Practical application of the industrial screening and optimization method

The industrial screening and optimization method in the format of the ISO 14040 protocol has been applied in a study about the Canadian oil sands industry and its environmental impacts. Despite the lack of information on some parts of the oil sands chain and although further studies in this field are required, the study has resulted in a representative overview of inherent environmental indicators of the oil sands technology chain. These inherent environmental indicators (together with financial and social indicators) can serve as input to an industrial optimization model of energy systems. To develop such a model, similar studies about other energy technology chains are required. Because only a single technology chain (oil sands) could be studied in this thesis phase 4 (optimization) and phase 5 (interpretation) could not be tested. To study phase 4 and 5, multiple technology chains are required.
9. Recommendations and discussion

9.1 Practical suitability of the industrial screening and optimization for energy technology chains

The case study about oil sands technology and its environmental impacts has led to the conclusion that (as far as is known to the author) there are no scientific studies or methods that try to model environmental impacts from the entire source-to-service-to-sink oil sands chain. A quick literature scan by the author on other energy source-to-service-to-sink chains (e.g. conventional oil, wind or solar power) and their environmental impacts supports these findings. However, (LCA, EIA) studies of individual elements (building blocks) within energy chains are abundant in literature. These studies had to be combined in order to give an indication on the (inherent) environmental impacts of the oil sands technology chain. Besides lack of information on some parts of the chain, this was relatively easy and when more effort and cooperation from technical and environmental experts of oil sands are combined, a good indication on environmental impacts of the entire oil sands technology chains is possible. In order to incorporate several energy technology chains (conventional, unconventional, and renewable) into one optimization model a lot of effort (e.g. studies) will also be required to model inherent environmental indicators of these technology chains.

The industrial screening and optimization method with underlying (LCA) framework of environmental business pressures is much more complex and more time-consuming than, for example, application of sustainable production indicators in an optimization model. However, as been described before, the main drawbacks of the sustainable production indicators are their low transparency and the possibility of environmental impact trade-off. The indicators for industrial optimization proposed in this study make targeting specific environmental impacts possible and gives a complete and transparent overview of environmental business pressures and their potential impacts. The industrial optimization method will be stronger than the sum of these individual studies, because the probability of environmental impact trade-off between individual elements of the energy technology chains is less and if trade-offs occur they will be more transparent.

9.2 Critical endnotes

This study about environmental indicators in the industrial screening and optimization method is only one core element in the total screening and optimization method. Besides environmental indicators, the triple bottom line optimization method also requires social and economic indicators as inputs. Similar studies on social and economic indicators are therefore required. Furthermore, (mathematical) optimization models need to be developed that can process and optimize triple bottom indicators (phase 4 in the industrial screening and optimization method). Finally, studies are needed on how to interpret, value, weigh and present the results of the optimization models. For example, interpretation and presentation could be supported by spider diagrams or multiple dimension (e.g. 3D) models and valuing and weighing of indicators could be implemented by monetarization or boundary conditions. Studies should also focus on
how to translate outcomes of the optimization model into practice through adaptive innovation. A system cannot sustainably develop in isolation. Therefore, the implementation of sustainable solutions cannot be assigned to business exclusively, but will require a joint effort of authorities, businesses and society. A problem that might arise when implementing sustainable solutions is the fragmented character of most source-to-service-to-sink technology chains. Entire source-to-service-to-sink technology chains (both up and downstream processes) are seldomly possessed by a single company, which is why individual business interests might obstruct implementation of sustainable solutions. Therefore, this would require cooperation of firms and corresponding legislation and incentives from governing bodies to facilitate internal impact trading within source-to-service-to-sink technology chains, such as in carbon cap and trade.

Besides, factors that should be taken into account when implementing sustainable solutions in practice are cost-effectiveness, feasibility and social acceptability (Schoot Uiterkamp and Vlek, 2007). One should also acknowledge that optimizing on the triple bottom line will be a weighting and therefore will not solve environmental problems entirely, although win-win-win solutions are possible. Human activities make it simply impossible to leave the environment in its untainted state, although a sustainable way of life is possible. Environmental impacts from human activities can be reduced to the level in which there is minimum harm to the natural environment as well as to human society.

Finally, the here proposed industrial screening and optimization method cannot replace existing environmental assessment methods in business, but should be seen as an addition to these existing methods. The industrial screening and optimization method should be seen as an initial phase to the application of micro-level methods, such as Environmental Impact Assessment (EIA), Environmental Management Systems (EMS) and Life Cycle Analysis of (LCA) processes or products.
References

Appendices

Appendix 1. The Pressure-State-Response framework

Appendix 2. Life Cycle Assessment framework (ISO 14040)
Appendix 3. The complex cause-impact chain of land and resource use

Source: Udo de Haes et al. (2002)
Appendix 4. Example of a spider diagram
Appendix 5. Oil sands upgrading process