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CLARIFICATION OF SUSTAINABILITY CONSEQUENCES OF MANUFACTURING PROCESSES IN CONCEPTUAL DESIGN

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ABSTRACT

In the conceptual design of aircraft jet engine components, not only the product architecture and dimensions are set but the associate manufacturing processes are also defined. From a design decision point of view it is critical to identify and characterize the consequences of alternative solutions. This paper reports on a case, where a milling process needed to be selected in an early design phase of a jet engine component. An Electro-Chemical Milling process was considered but its impact on sustainability needed clarification.

An approach that combined a simplified Environmental Impact Assessment with a Strategic Sustainability Assessment was used. The main finding and contribution from the work is a method that helps to clarify consequences of sustainability-related issues by combining the two analysis tools with a risk analysis implementation. The results reveal that once the consequences can be clarified, increased attention and understanding are gained.

Keywords: sustainable manufacturing, strategic sustainability assessment, risk assessment, conceptual design, decision support

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1 INTRODUCTION

Design decisions made in the early stages of development significantly limit the options for subsequent design options, such as which manufacturing processes that can be used. An obvious challenge is that the greater part of a product's life cycle cost and environmental impact is determined in the early phases (Ullman, 1997; McAloone 2004)) but the information on relevant manufacturing processes are rarely complete at this stage. This paper reports on a real life situation, where a manufacturing process needed to be selected in an early design phase of a jet engine component. The example highlights a situation that contained some uncertainties of the sustainability impact and its seriousness level for one particular manufacturing process. To clarify the potential sustainability problem, an in-depth strategic sustainability assessment (including environmental, social and economic aspects) for this manufacturing process was added to an eco-design tool to provide support for a decision.

The main challenge addressed in the paper is that findings from an environmental impact assessment in the early design phase, cannot clearly state consequences and therefore strategic decisions cannot be made using these findings. The main contribution of this paper is to present an approach and a new method that can be applied to clarify the consequences for decision makers in early product development.

1.1 The significance of sustainability aspects for jet engine designs

Market competition and the evolution of jet engine designs over time drive the need for more optimized products to a lower cost without compromising airworthiness. The efficiency of new engines contributes to less environmental impact in operation, yet there is a long way to go before these engines can be considered 'sustainable'. Within the aeronautics industry, there are specific sustainability targets set out by the Advisory Council for Aeronautics Research in Europe (ACARE, 2002; 2004) with one of the high-level targets being an "ultra-green air transport system." At GKN Aerospace Engine Systems, former Volvo Aero, (GKN) a leading manufacturer of aero engine components, this has decomposed into concrete design targets like light weight, noise/emission reduction and high reliability.

The majority of opportunities to influence the sustainability performance of products present themselves come when the product is designed – far before it is created or put into use. The functional requirements of the engine as a system are decomposed and component design requirements are derived. Such functional requirements typically result in the need to use new, more durable and high performance design solutions and alloys in the engines since higher temperature and pressure inside the engines typically are needed to achieve the desired performance targets. More advanced materials require specific manufacturing processes, and in order to balance and achieve a robust design and production process, there is a need to improve decision making tools in early phases of the design.

Focusing on the engineering design situation of a jet engine component, where conceptual design decisions need to be made, the distance between societal trends and challenges and the specific design targets may appear large. Any high level ambition or trend needs to be decomposed and made explicit and precise in order to be applicable to guide design decisions.

1.2 Design for sustainability support tools

Several methods, tools and concepts have been developed, intended to facilitate an integration of environmental aspects into the product development process. Different types of eco-design tools can highlight potential environmental problems and facilitate a choice regarding different environmental aspects (Byggeth & Hochschorner 2008). In Lozano (2012), an analysis of the sixteen most widely used initiatives (e.g. life-cycle assessment, eco-design, cleaner production, corporate social responsibility, and sustainability reporting) are analyzed as to how well the sustainability dimensions are addressed and how the different initiatives are connected to the company system. Lozano concludes that relying only, or even mainly, on one initiative can result in a limited and narrow contribution to sustainability, with limited coverage of the company's system.

The most common support tools used in companies today for guiding decisions on sustainability issues or conducting sustainability assessments are based on legislations of today, such as the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH), or known global environmental impacts. Awareness of the global sustainability constraints of today is necessary as it gives concrete requirements and sets the minimum limits for what the companies are allowed to do today. However, in order to be strategic and avoid running into negative surprises and blind alleys in the future, a long-term perspective also needs to be added. Hence, long life complex products with long production periods, i.e. 20-30 years, will also need to be adapted to global future sustainability constraints and therefore a long time perspective is necessary.

The challenge to account for future situations partially involves an uncertainty about which conditions that will be decisive, and, partially, the fact that forecasts and predictions of the future tend to be general and high-level oriented. To include a long-term perspective, backcasting from a future sustainable society can be used. In short, backcasting means imagining success in the future and then looking back to today to assess the present situation through the lens of this success definition and to explore ways to reach that success (Robinson 1990; Dreborg 1996; Vergragt and Quist 2011, Quist et al. 2011). Backcasting gives support in being strategic in the development towards sustainability (Gaziulusoy et al. 2012), in part because it enables moving in the right direction via "flexible platforms" in order not to move into "blind alleys" that might prevent continued progress (Ny et al. 2006).

Also, the success definition from what to backcast from needs to be defined. The Framework for Strategic Sustainable Development (FSSD) includes backcasting from a success definition of a sustainable society which is intended to be applicable now and in the future. The FSSD also specifies a generally applicable definition of sustainability expressed as first-order principles (Holmberg and Robèrt, 2000). In essence, these first-order principles act as a root cause analysis for social and ecological issues. This root cause analysis encourages open-ended and non-prescriptive co-creation towards sustainable solutions that do not miss or give preference to certain sustainability aspects.

1.3 Sustainable manufacturing in design

One aspect of importance for manufacturing companies is the need for ever increased precision in robustness of the product and its realization process. This is mainly an effect of introducing more optimized designs and reducing margins. Products, and production processes, are costly to change once they have been set. There is a major driver for identifying and accounting for any condition that may result in non-robust products and processes as early on as possible in the design phase. The global strive for a sustainable society continuously enforces new restraints, but also opportunities, for manufacturers to meet. Sustainability has received increased attention by the manufacturing industry and there is an interest in, for example, how to implement sustainability information (Aschehoug and Boks, 2011). Another research group (Bohm et al. 2010) has worked to bring environmental and life-cycle aspects into the conceptual and early phases of design, through computational concept generation and life-cycle assessment techniques. Their goal is to develop an automated mechanism for an environmental analysis in early design to more easily integrate an environmental assessment throughout the entire design cycle. An alternative and initial approach integrating sustainability into the conceptual design process has been suggested by Thompson et al. (2012). This approach addresses two problems: 1) robustness of a "sustainable design space" in the same manner as the early steps in a set-based concurrent engineering approach, and 2) alignment of sustainability considerations throughout a generic design cycle. The suggested approach has adopted the set-based concurrent engineering, that systematically builds knowledge, about multiple design concepts and then successively eliminates concepts, so that the finally decided concept is robust, which reduces the risk of late changes (Sobek et al. 1999). Rio et al. (2011) present another approach to get sustainability closer to the engineering environment, and Chevalier et al. (2011) present an effort to do life-cycle assessments (LCA) more available.

In the suggested approach by Hallstedt et al (2013), sustainability criteria is identified as a key factor to identify the sustainability constraints to be used in the product requirement list. Similar ideas to define criteria or measurements, but specifically for sustainable manufacturing, are discussed in a review study of the development and on-going research in the area of sustainable manufacturing by Haapala et al. (2011).

Even if it is desirable to make design decisions that facilitate sustainable manufacturing, it is still important to have assessment tools that can provide guidance of manufacturing processes when needed. It is also recognized that although issues with sustainability and life-cycle challenges can be identified in design phases, their consequences are difficult to assess. The results of early sustainability assessments of manufacturing alternatives are weak from a decision point of view.

2 STRATEGIC SUSTAINABILITY ASSESSMENT OF ELECTRO-CHEMICAL MILLING

The need is to improve decision making by developing an approach to better clarify consequences of sustainability issues already in conceptual design. The industrial case presented is used to exemplify the situation and as means to justify the suggested approach and a proposed new method.

The case describes a design situation where the project team was to decide on an architecture for a new high-temperature jet engine component. The functional requirements were challenging and the conceptual selection in practice also decided most of the pre-requisites for its manufacturing.

In order for the development team to make a decision of which manufacturing process would be a good investment for the company in both a short-term and long-term perspective, an environmental impact assessment was undertaken. The engine component was assessed for its full life-cycle, i.e. from raw material extraction to the disposal phase, where hot-spots (serious impact potentials) of environmental concerns were identified. In this particular case there were some uncertainties of the seriousness level for one particular hot-spot, the electro-chemical milling (ECM) process. To clarify the potential sustainability problem, an in-depth strategic sustainability assessment (including environmental, social and economic aspects) for this manufacturing process was added to the environmental impact assessment to provide support for a decision.

In short. the idea was to combine two different methods, first to identify hot-spots, then to assess sustainability impact of the same hot-spots;

i) Step 1: Environmental Impact Assessment (EIA) of the product's life cycle,

ii) Step 2: Strategic Sustainability Assessment (SSA) of the selected hot-spot

Combining these methods enabled better decision making in the design team, and each step will be explained in more detail in chapter 3 and 4 respectively. The ability to assess consequences was added to the already available EIA, and the design team could act on the improved decision base that had been derived. Chapter 5 discusses how the method can be further improved.

Research methodology wise, this research has been performed using participation action research (Ottosson, 2003). In this study the main author was part of the work and explored, objectively described and learnt about the case and then actively influenced the work at the company by using the knowledge obtained through research in the field.

3 STEP 1: ENVIRONMENTAL IMPACT ASSESSMENT

3.1 Background of the Environmental Impact Assessment

The Environmental Impact Assessment (EIA) is a simplified, qualitative, life-cycle assessment and eco-design tool, aiming at identifying and assessing significant environmental impacts generated by the product's life cycle, from the resource extraction phase to the end of life, early in the product development process. The purpose is also to give corrective/recommended measures to decrease or avoid the environmental impacts and consequently to improve the environmental performance of the product. (HRM/Ritline et al. 2000; Lindahl et al. 2000)

The EIA support tool has been under development since early 1990 and a Swedish industrial consortium (Verkstadsindustrier) has initiated a further development and education of the support tool (Lindahl et al. 2000). This resulted in an implementation of the support tool as a complement or alternative to a quantitative life-cycle assessment in several larger companies (Hallstedt et al. 2012). At GKN, this is included in the standard support tool portfolio (Hallstedt and Thompson, 2011) and therefore used in this case to investigate the environmental impact for the jet engine component.

3.2 Working process of the Environmental Impact Assessment

The EIA method is already established and practiced in the company. The EIA was lead by an environmental engineer and the first step was to set up and prepare for the assessment. This was done by defining the studied system and the working group, as well as to collect data (such as legal, internal/external environmental requirements, technical requirements). The next step was to carry out the assessment of environmental impacts using a form based on rating with a scale from 1 to 3 (where '3' has the highest significance) for the four following criteria:

- Severity: from negligible negative damage (1) to long-term or permanent severe negative damage (3)

- Steering documents: from no requirements in steering documents or quantity/occurrence of the activity that are negligible (1) to requirements that are regulated in steering documents and quantity/occurrence that are above a valid limit like a maximum level of emissions of carbon dioxide for instance (3),
- Interested parties: from no negative effect on the company's environmental reputation (1) to severe damage to the company's/corporate groups' reputation regarding the general public (3),
- Improvement potential: from good and quick improvement (1) to little/no possibilities of improvements (3).

The ratings of the criteria (done independently) were discussed in the working group and set by the environmental engineer. After the rating process, recommendations to identify corrective/recommended actions were decided from the working group. The last step in an EIA is to follow up on the recommendations and measures to see if these have been achieved.

3.3 The result from the Environmental Impact Assessment

The EIA of the jet engine component resulted in a few hot-spots, whereof the ECM was indicated as such (see Figure 1). In contrast to the other hot-spots it was difficult to find an easy recommendation and corrective measure for ECM without changing the manufacturing process to an alternative solution, in this case mechanical milling. To choose the mechanical milling solution would result in some investments cost as some work already had taken place in terms of design adaptation and supplier investigation of the ECM. There were also some uncertainty in the rating of the ECM and some unanswered questions of its seriousness level, which indicated a need for an in-depth study of the ECM process for the component.

The main questions that needed to be answered and investigated further from a sustainability perspective were:

- If and why the ECM process generated hexavalent chromium, nickel – and lead particles when applied for nickel-based alloys?
- Could these emissions be avoided?
- If not, how and what sustainability consequences are likely in both a short- and long-term perspective?

Well-known already today is the fact that hexavalent chromium (Cr VI) and nickel (Ni) are considered to be of great severity for both ecological- and health perspectives, as these are carcinogenic, allergenic and toxic.

Phase	Activity	Env. aspect	Env. impact	Severity (1-3)	Steering docu-ments (1-3)	Intere-sted parties (1-3)	Possibility for improv-ement (1-3)	Comm ents/ Recomm-endation	Respons-ible
Produc-tion at the supplier	ECM process	Emissions to water/ land & Hazar-dous waste (sludge from the electro-lyte treat-ment)	Toxic impact on human beings. Ecotoxic impact on organisms Biodiver-sity decrease	2-3? (Max rate 3 means: long term and severe negative damage)	2-3? (Max rate 3 means: require-ments regulated in steering document)	2 (Max rate 3 means: severed damage to company's reputa-tion)	2-3? (Max rate 3 means: little possi-biities of improve-ments)	Uncert-ainty of serious-ness level. Need further investiga tion	Project leader

Figure 1. The rating of the electro-chemical milling (ECM) process in the Environmental Impact Assessment (EIA) for the jet engine component.

From an engineering design point of view, the EIA method readily identified critical issues (hot spots). The method did not provide enough support for active design decisions. Further investigation was needed.

4 STEP 2: STRATEGIC SUSTAINABILITY ASSESSMENT

4.1. Background of the Strategic Sustainability Assessment

A Strategic Sustainability Assessment (SSA) was introduced in the research study as a means to clarify and better understand sustainability consequences. The SSA is based on guiding questions inspired from a previously developed Method for Sustainable Product Development (MSPD) (Byggeth et. al. 2007). The main idea of using guiding questions was to avoid detailed rules and prescriptive guidelines. The purpose was instead to raise the awareness and knowledge about sustainable manufacturing problems and opportunities among project leaders and product developers and to open up for a creative dialogue and innovation within basic sustainability constraints.

Strategic sustainability is here defined as backcasting from sustainability principles, which the guided questions were based on. These sustainability principles state that in a sustainable society, nature is not subject to systematically increasing… (1)…concentrations of substances from the Earth´s crust, (2)…concentrations of substances produced by society, (3)…degradations by physical means, and, in that society, (4) people are not subject to conditions that systematically undermine their capacity to meet their needs (Robèrt et al. 2002). These principles are designed for "backcasting" described in section 1.2. Also a product life-cycle perspective (from raw material extraction to the disposal phase) and an economical perspective was considered in the development of the guided questions for the strategic sustainability assessment, see Figure 2. In contrast to the MSPD's generic questions, these questions were case specific and aimed at asking relevant questions for the hotspot identified.

Requirements and risk perspective	Ecological perspective SP1-3	Social perspective SP4	Economical perspective
Short term	Guiding qestions based on: i) socio-ecological sustainability principles, ii) economical perspective iii) a product life cycle in relation to short-and long term requirement- and risk perspective		
Long term			

Figure 2. Theoretical base for the development of the guiding questions. SP1-3 means ecological sustainability principles and SP4 means social sustainability principle according to the definition suggested in Robèrt et al. (2002).

4.2 Working process of the Strategic Sustainability Assessment

The SSA was conducted in several steps:

First, in order to clarify *if and wh*y the ECM process generated hexavalent chromium, nickel – and lead particles when applied for nickel-based alloys; the material flow, potential emissions, waste treatment as well as rest-product treatment were investigated. The investigation was made mainly through a literature review and meetings with potential suppliers of the ECM process. This information also gave answers to *if* it was possible to avoid these emissions and how to maximize the possibilities to keep these emissions isolated and in closed technical loops.

Second, in order to clarify *how and what* sustainability consequences that would be likely in both a short- and long-term perspective, as well as to sort the information from the first step, the guided questions were used. See Figure 3 for some examples of guided questions used for the case. To answer the questions an additional investigation of requirements from a variety of sources was made. Examples of sources were i) company requirements & goals, e.g. corporate documents and environmental policies; ii) industry requirements and goals, e.g. within the aerospace industry, the Advisory Council for Aeronautics Research in Europe (ACARE); and iii) existing regulations at national and international levels, e.g. REACH. Most answers for the short-term perspective did relate to present environmental, social and economical requirements, such as documented requirements stated by the company, customers, and in legislation, while the answers from a long-term perspective was more in terms of reflections and logical reasoning.

Requirements and risk perspective	Ecological perspective SP1-3	Social perspective SP4	Economical perspective
Short term	Are there any indications for restrictions regarding CrVI in any of today's requirements or legislation?	Are there any risk with accidents and leakages over time? What are the likely consequence if an accident happens? In the daily work, is the working environment safe?	Are there any advantages – or disadvantages for investing in a ECM today for this specific product component?
Long term	Will there be an accumulation of Cr in any of the life cycle phases? Is it possible to keep CrVI in closed technical loops over time ?	Is it a risk that there will be stricter regulations and requirements in the working environment area regarding CrVI?	Is it any advantages – or disadvantages for investing in a ECM in future? Is it a risk that there will be stricter regulations and requirements regarding CrVI?

Figure 3. Examples of guiding questions used in the Strategic Sustainability Assessment of the Electro-Chemical Milling Process.

4.3 The result from the Strategic Sustainability Assessment

The results from the short-term time perspective showed citations from corporate steering documents suggesting precautionary measures if possible. From the economical short-term time perspective it could however be more beneficial to choose the ECM, as already some investments had been made due to late awareness of the potential problem with hexavalent chromium and due to the fact that the cost for alternative manufacturing processes was a bit more expensive. However, the ECM process would likely be of an economical disadvantage in the long-time perspective if the company had to change to another manufacturing process due to tougher legislation in the future. Given that the ECM process is needed for a 30-year period and given the already severe requirements and upcoming ban, there is a risk that there is no long-term benefit in investing in the ECM, even if it is lower investment cost of today. From the socio-and ecological perspective, the guided questions highlighted some aspects to consider such as the importance of company image, and the risk of leakage and consequences if that would happen.

The final result of the assessment was a summary of reasons and recommendations based on the SSA. In this case, it resulted in seven reasons for not investing in ECM. Examples of reasons were: i) material lists show a warning for a ban of processes that involve Cr VI; ii) as Cr VI is carcinogenic and allergenic it is, from a social perspective, not a process that can be justified if there are alternatives to use; iii) according to the precautionary principle alternatives should be chosen when there are environmental- and health risks; iv) given that the ECM process is needed for a 30-year period and given the already severe requirements and upcoming ban, there is a risk that in the long run not to take advantage of an investment in ECM, v) there is also from an economic perspective a certain risk with having only a few sub-contractors that can provide this process and a costly investment in new tools for a process that is not very developable.

The final recommendation was therefore to consider the short-and long-term consequences and preferably use the alternative mechanical milling process instead, that involves only one hazardous substance (nickel), rather than to use the ECM process. This was also the decision that was taken in the project development group.

5 A NOVEL METHOD FOR CLARIFYING SUSTAINABILITY CONSEQUENCES

The result from these two assessment steps gave a better basis for development decisions compared to the EIA only. Despite some investments and a short-term economical benefit, the work with ECM was stopped and the final recommendation from the assessment to preferably use the alternative, the mechanical milling process, was instead the main alternative.

From an engineering design point of view, this in-depth investigation clarified sustainability impact consequences of the proposed manufacturing process and suggested an alternative manufacturing process. It provided the necessary clarification of consequences of the identified hot-spots and provided enough clarity to constitute a decision basis for the design team.

Despite the successful introduction of the two-step method described in this case, there remains a need to further improve the method. The design team need a way to position the described methods within their decision-making environment. The most straightforward approach is to strengthen the already existing risk assessment approaches, since these are well known to designers and decision makers, and focus on even further clarifying the consequences of identified risks. The risk assessment should be based on possible consequences, the likelihood of these to happen, and estimated costs if they happen. The reason for adding a quantitative assessment step is that it could support the understanding of the result from both short- and long-term perspectives, enhance a comparison with other risks, and facilitate the communication of the result to the engineers. Thus, the suggested new method largely puts the sustainability impact into a perspective that can be compared with other risks.
To avoid changes late in the product development stages, a standard assessment process in line with the above described method is suggested for all the manufacturing processes that form part of a company's manufacturing platform. In this way, the manufacturing processes are at an early stage evaluated from a strategic sustainability perspective, and will support the development of a robust manufacturing company platform.

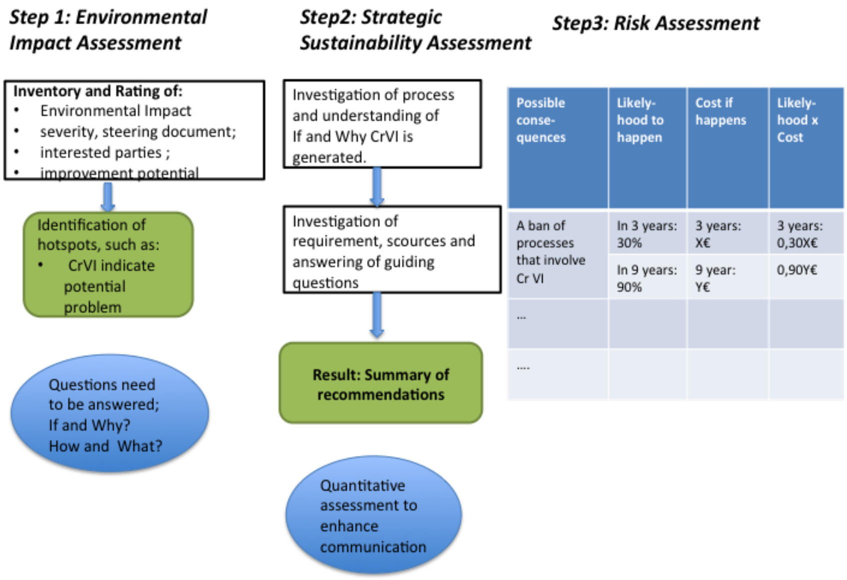

Figure 4. Support tool for Sustainable and Robust Manufacturing consisting of three steps; an Environmental Impact Assessment; a Strategic Sustainable Assessment, and, a Risk Assessment

6 CONCLUDING DISCUSSION

The conclusion from this work is a novel method that helps to clarify consequences of sustainability-related issues by combining two types of analysis tools with a risk analysis implementation. The results reveal that once the consequences can be clarified, increased attention and understanding are gained.
The conclusion made from this work is that through introducing a two-step approach, where first the hot-spots are identified and then assessed from a strategic impact perspective, the design team obtained enough clarification to make well-informed decisions based on deeper understanding of the consequences of their decisions. A third step is proposed that would establish the two-step method within the more well-known risk assessment process. The advantage would be the harmonization with "similar" issues where senior decision makers can compare sustainability-governed risks with other risks in a similar fashion.

6.1 Strengths of the approach used for guidance of manufacturing processes

There are several reasons for arguing that this suggested method can give guidance for sustainable manufacturing. These are:

- *A full sustainability perspective is covered:* This means the inclusion of both an ecological and a social sustainability perspective. The social sustainability aspects (e.g. protection of internationally proclaimed human rights, no toleration of any form of forced, compulsory or child labor, etc.) are as important as the ecological perspective. The reason is that product solutions need to be supported on a market for a significant period of time and dependencies on unsustainable suppliers come with a significant risk as this affects the long-term company reputation and image, investment plans, quality control and efficiency.

- *A definition of sustainability provides guidance:* To have a common view on sustainability (Broman et al. 2000, Johnston et al. 2007) is identified as one of the key factors identified for development organizations to strengthen their ability to support a sustainable development process. In our suggested approach, the overarching sustainability principles are used as a definition of sustainability and are also used to develop the guided questions in the SSA tool.
- *Short- and long-term perspectives are covered:* A combination of tools with a forecasting and a backcasting approach has the advantage of including aspects of today together with risk aspects of the suggested solution from a future sustainable society perspective. The long-term perspective is not normally considered in support tools used in the product development teams, which makes it harder to take actions today for issues that might come up later (Hallstedt et al. 2013). At the same time, development towards a sustainable society in the future needs a long time planning perspective. In Lozano (2008) it is stated that a longer time perspective is important as a dimension in the understanding of sustainability, but it is not clearly covered in most of the used representations of sustainability.
- *A comparable measurement is given:* Earlier research has shown that a risk approach is suggested when planning for sustainability (Boyle, 2004). Risks related to sustainability have been considered to have a significant impact on businesses according to WBCSD, 2004 (World Business Council for Sustainable Development). Gaziulusoy et al. (2012) mean that if the company understands how the actions of product development, on an operational level, are connected to the company strategy and puts that in a context of a vision for a sustainable society, a proactive behavior to address sustainability issues in companies can be encouraged. An awareness of sustainability risks for their business will function as an incentive to identify new technological and organizational innovation opportunities (Gaziulusoy et al. 2012).

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