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Assessing Sustainability and Value of Manufacturing Processes: A case in the aerospace industry

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Abstract:

In spite of the growing awareness and significance of accounting for sustainability aspects in product development, design decision support is still immature in this end compared to other decision support areas, such as product performance and manufacturability. This paper proposes a novel decision support method that combines qualitative sustainability assessment techniques with a quantitative analysis, without losing transparency and still covering a full sustainability perspective. The aim is to contribute to an understanding for how to enable value assessment of sustainability issues already in early product development situations. The method, named Sustainability Assessment and Value Evaluation, combines two qualitative sustainability assessment techniques with a quantitative Net Present Value analysis based on alternative future scenarios. A case study, related to the development of a new high-temperature aero-engine component, illustrates both how the sustainability assessment identifies hotspots and clarifies potential sustainability consequences for a new product technology, and how Net Present Value is used to assess alternative solution strategies based on the hotspot, to facilitate early stage decision-making in design. The paper argues that the method serves two main purposes: i) to make sustainability consequences more concrete and understandable during design concept selection activities, rather than to have an exact measurement, and ii) to simplify and prioritize, systematically asking what is important in the sustainability analysis, rather than to reduce the sustainability problem. The method allows undertaking the sustainability assessment in a more structured way than what happens today in preliminary design, through scenario building based on socio-ecological assessments, including back-casting to cover the longer time perspective. In addition, the Sustainability Assessment and Value Evaluation-method provided the design team of a means for displaying sustainability consequences on an equal basis with other decision support tool results.

Keywords: Strategic Sustainability Assessment, value assessment, conceptual design, engineering design, aerospace.

1. Introduction

The implementation of decision support for sustainability in product development and manufacturing is a matter of considering socio-ecological aspects in a systematic way, rather than picking ad hoc measures or focusing on one aspect in a reductionist way (Hallstedt et al., 2013b). Sustainability aspects need to be considered in a life cycle perspective (raw material

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extraction, production, distribution, usage & maintenance, end-of life) (Thompson et al., 2012) and in relation with other aspects, such as functionality and manufacturability. Examples of sustainability issues in the product development process are: What are the sustainability implications of the materials and chemicals currently used in the forthcoming products and production processes? What are the sustainability implications of the manufacturing processes used? How can the manufacturing platform develop to generate a better working environment? How can the product be designed to reduce the energy usage? How can the product be designed to be recycled and to keep materials in closed-loops within the value-chain?

Product development and manufacturing processes have been developed stressing the ability of obtaining high-quality products at minimum costs, to promote the competitiveness of the company. This suggests that efforts to meet environmental regulations should be kept to the barely minimum, as going behind this will increase cost (O'Brien, 1999). Nowadays this attitude is likely to change, because awareness on environmental problems and the impacts of products on society is growing (Tukker et al., 2008; EEA, 2014). Sustainability matters are increasingly receiving attention among consumers, who want to make the right choices when buying products and services. To remain competitive, manufacturers need at least to understand consequences of sustainability aspects (risk perspective), and may even actively use insights in these trends as a driver for new products (innovation perspective).

Already today some companies recognize sustainability issues as business opportunities rather than undesirable pressing situations (Bonini and Görner, 2012). Although in the short term improved environmental efficiency may increase costs, in the long term it is expected to show a positive impact on financial performances (O'Brien, 1999) and competitive advantage (Yang et al., 2010). This is because, as far as material, energy and waste disposal costs rise, the cost of inactivation may be higher than making the improvements themselves. This is particular true for companies dealing with product that are produced during a long period of time (i.e. more than 20 years) and that need to be supported for much longer after production has ended. In such cases, the selection of technologies and product/process solutions is driven by considerations grounded long into the future (Hallstedt et al., 2013b).

One of such industries is aerospace, which features the introduction of advanced technologies with long life cycles. Sustainability has therefore become one of the main drivers for technology development in this domain. The Strategic Research Agenda published by the Advisory Council for Aeronautics Research in Europe (ACARE, 2011) identifies sustainability as one of the most significant drivers that will influence current and future solutions for new airframes and aero-engines. Commercial aerospace has experienced a rapid growth in terms of passengers: air traffic has doubled every 15 years in the past, and is expected to double again in the next 15 (Airbus, 2013). The "Ultra green air transport system" defined as a major high-level target for research in aviation (ACARE, 2011), pointing towards reducing the environmental impact of aircrafts and associated systems during their life cycle: from manufacturing to operation, maintenance and disposal phase (Witik et al., 2012).

In parallel to the evolution of strategic initiatives, the design activity needs also to shift focus, and this highlights gaps in established means for decision support. What criteria and indicators shall, for example, be used to assess alternative solutions from a sustainability point of view? While literature emphasizes the impact sustainability has on a company's costs as revenues, empirical observations show that designers tasked with the early-stage selection of a product/technology concept find it difficult to realize the opportunity for value creation

generated by a sustainability-friendly choice (e.g. Hallstedt and Isaksson, 2013). A better understanding could be reached by aligning sustainability metrics and product metrics when approaching critical design decisions. In this spirit, the ambition of the design team is often to cover sustainability with quantitative indicators expressing the economic impact of sustainability choices.

Recent attempts to integrate sustainability with a value-based view remains at an organizational strategy level, and do not dive into a design situation (Willard, 2012). To spotlight the value creation opportunity of a sustainable choice, a step change is required to integrate sustainability considerations into the preliminary stages of design (Bey et al., 2013). Identified sustainability criteria need to be taken into consideration with the same importance as any other system requirement in a product-planning phase (Waage, 2007; Hallstedt et al., 2013a). A fundamental problem here is the mix of qualitative methods that can provide a good overview, with quantitative methods typically needed in e.g. economic value situations.

2. Purpose and Objectives

The purpose of this work is to strengthen the decision support for design teams that need to value aspects influencing sustainability behavior of products and processes. The objective is to bridge the gap between qualitative assessment models that account for sustainability consequences with more quantitative tools able to express the value consequences of design decision alternatives. The work focuses on the earliest phases of the design process, where the impact on the entire product life cycle is high and the information available is immature.

The paper is organized as the following. The result from a literature review is presented in section 3, followed by a description of the research method in section 4 and findings from empirical studies in section 5. The novel method proposed, named Sustainability Assessment and Value Evaluation (SAVE), which is intended to inform early stage decision makers about the value-related consequences of their sustainable design options, is described in section 6. Section 7 presents the application of the SAVE-method for the development of an aero-engine component technology. The case has been used as main reference to discuss and verify SAVE with designers and process owners in co-located industrial workshops, as described in sections 8. Further discussions and conclusions from this research are elaborated on in sections 9 and 10.

3. Literature review

The literature review covers the field of environmental impact assessment, life cycle assessment, and other tools and methods for sustainable design and sustainable manufacturing. The section ends with a short review of value-driven design in relation to sustainability.

3.1. Environmental impact assessment and life cycle assessment

Environmental Impact Assessment is a procedure to support decision making with regards to environmental aspects of activities. The purpose of the assessment is to ensure that decision makers consider environmental impacts when deciding whether or not to proceed with a project (EU, 2011). In product development, EIA identifies significant environmental impacts generated by the product's life cycle from the resource extraction phase to the end of life.

From this, it proposes measures to adjust impacts to acceptable levels or to investigate new technological solution. It is often regarded as a local, point-source oriented evaluation, which takes into account time-related aspects, the specific local geographic situation, and the existing background pressure on the environment (Tukker, 2000). EIA is criticized for excessively limiting its scope in space and time, and to focus on short-term, direct and immediate effects on sustainability (Lenzen et al., 2003). Also the ability of EIA to influence decisions is believed to be rather limited, mainly because it is intended to be a decision-aiding tool rather than decision-making tool (Jay et al., 2007).

Life Cycle Assessment (LCA) (ISO, 2006) has been proposed (Manuilova and Suebsiri, 2009) as a natural way to complement EIA with quantifiable information, and hence support the decision-making process in a more structured way (Lozano, 2012). Even branch-specific LCA-tools with common databases have been developed with the aim to enhance eco-design activities, e.g. for the aerospace industry the simplified LCA tools ENDAMI and LEAF have been developed within the EU funded research program called Clean Sky (see: http://cordis.europa.eu/result/rcn/147382_en.html). LCA offers a holistic tool encompassing all environmental exchanges (i.e., resources, energy, emissions, and wastes) occurring over the product/service life cycle (Carvalho et al., 2014). Stand-alone LCAs have been conducted across a number of different industries, particularly in automotive applications (Finkbeiner et al., 2006; Zah et al., 2007). Other life cycle methods such as Life Cycle Costing (e.g. Krozer, 2006) and Life Cycle Engineering (e.g., Asiedu and Gu, 1998) are used to guide engineers and designers in making more informed decisions during product development and to achieve an optimum between cost and environment. Examples of LCE application include the material selection process for an automotive fender application (Ribeiro et al., 2008) and the selection of a mold manufacturing method (Pecas et al., 2009).

Despite the common use of LCAs, they are claimed to be time consuming, expensive and data intensive (Hale, 1996), and to eventually become a vast, cumbersome exercise that gets bogged down in excessive detail (Thiede et al., 2013). Also, they mainly focus on the environmental dimension of sustainability, not covering the complete sustainability picture. Since EIA and LCA are mainly “assertive” methods that build on the historical information available in the company databases, they are best utilized when the product architecture and its distinguishing features are already frozen. This is also one of the reasons why the use of these methods is often associated with “late discovery” of sustainability issues, and hence accompanied with rework and cost overruns.

In the domain of manufacturing, sustainability considerations are often linked to economic growth indicators (Joung, 2012), ranging from the overall net profit earned by the organization (Hu et al., 2009), manufacturing costs (Witik et al., 2012), or Return On Investment (ROI) (Lee et al., 2014). Assessment methods often make use of Discrete Event Simulation (DES) to complement an LCA analysis (Thiede et al., 2013), or to more precisely account for sustainability indicators when dealing with Value Stream Mapping (VSM) (Paju et al., 2010). Bey et al. (2013) highlight that the industrial state of the practice shows a low degree of implementation of these quantification approaches in “real life” industry, mainly because they are intended to assess the life cycle cost of existing solutions, rather than to guide the conceptualization of new solutions. Another drawback is that these models are mainly static and disregard the dynamic behavior of industrial and ecological systems. Also, they are based on the data existing today and do not consider alternative future scenarios when it comes to design alternative analysis. Recent research proposes a dynamic LCA

approach (Pehnt, 2006) to build future scenarios based on forecasting (Laratte and Guillaume, 2014). Here, different LCA models are built including different exploitation scenarios for an industrial system, where the life cycle is very uncertain and there is lack of data (Cluzel et.al. 2014).

3.2. Combination of tools and methods for sustainable design and sustainable manufacturing

The integration of engineering and sustainability assessments, in order to facilitate engineering decision making, is a discussion topic becoming increasingly popular in literature. Zhang et al. (2013a) propose the use of system dynamics for modeling manufacturing systems, resulting in a combined approach utilizing principles of sustainable manufacturing and systems thinking. System dynamics was also used to support a sustainability and engineering optimization assessment in Byggeth et.al. (2007): by applying system thinking and using causal loop diagram, the authors identified the key optimization factors of a water jet cutting machine, both from a technical and sustainability perspective. Another approach for implementing ecodesign in the product development process is suggested by Pigosso (2013) using an eco-maturity wheel. These approaches all build on the idea of combining and adapting suitable environmental methods and tools as decision support for the specific company needs and maturity.

Recent studies show the benefit of combining assessment methods to include all the three dimensions of sustainability: economical, ecological and social. The combination of different tools and perspectives, integrated or concurrent, is claimed to give a clearer picture of the sustainability dimension and enhance decision-making in product development (Zhang et al., 2013b). As an example, Zhang and Haapala (2014) propose an approach that combines cost assessment; life cycle assessment, social life cycle assessment, pairwise comparison and an outranking decision-making method for evaluating a work cell from a sustainability viewpoint. These examples show that a mixture of different approaches and methods give a clearer picture of the problem and address different aspects as support for a more thorough decision.

3.3. Value-Driven design and sustainability

Sustainability requirements are not discussed exclusively in design, but are rather trade-off with other requirements, such as weight, purchase price, or fuel burn. These trade-offs are solved by looking at what the customers want, which is how much they “value” certain capabilities against each other. In the domain of Systems Engineering, Value-Driven Design (VDD) (Collopy and Hollingsworth, 2009) is proposed as a way to deal with such trade-offs and identify the most value-adding concept during preliminary design. Since “profitability” is by far the most intuitive dimension to assess the value of a system (Collopy and Hollingsworth, 2009), the “best” design is the one that ultimately produces the best overall economic value. Hence VDD optimization is often addressed by utilizing an objective function that produces a surplus value (or Net Present Value) score, a surrogate object for profit that represents an unbiased metric of the “goodness” of the final product. In the VDD process, firstly the designers pick a point in the design space at which to attempt a solution. Then, they create an outline of the design, which is elaborated into a detailed representation of design variables. Later, they produce a second description of the design instance, in form

of a vector of attributes that mirror the customer preferences or “value scale”. These attributes are assessed against an objective function, or value model, which gives a scalar score to any set of attributes. If the current configuration has a better score than any previous attempt, it is the preferred configuration to date. At this point, the design team can accept the configuration as their product, or try to produce an even better design by going around the cycle again.

While VDD does not yet consider sustainability explicitly in the value analysis (mainly due to the difficulty of translating it into monetary terms), recent attempts to introduce more qualitative aspects in the VDD process (Panarotto et al., 2013; Bertoni et al., 2014) show the opportunity of exploiting VDD to find a win-win-win situation where sustainable improvements are aligned with business advantages (Hallstedt et al., 2013b).

4. Method

Action Research (AR) (Avison et al., 1999) best describes how research was conducted. AR is an iterative process involving researchers and practitioners working together on a particular cycle of activities, including problem diagnosis, action intervention and reflective learning (Coughlan and Coughlan, 2009). It involves a spiral of routines, look-think-act or “learning circles”, in which researchers test a theory with practitioners in real situations, gain feedback from this experience, modify the theory as a result of this feedback, and then try again (Avison et al., 1999).

Previous exploratory and descriptive studies were used as a base for this research work. One of these studies was an initial explorative study conducted in collaboration with six large manufacturing companies (Hallstedt et al., 2013a). The definition and clarification of the problem domain for the specific objectives of the paper was further conducted in close collaboration with a large first-tier supplier of integrated metallic and composite assemblies for aero-structures and aero-engine products. This activity featured two empirical studies, which were conducted in collaboration with the first-tier supplier company.

The first empirical study aimed at gathering survey data from a group of 35 engineers and product developers, with regards to the ability of managing future needs for sustainability and value-driven innovation at the company. A questionnaire with 38 questions (a mixture of open and closed questions) was used. The aim was to uncover preferences and latent needs related to the use of sustainability assessment methods at the company today as well as to understand the process and main challenges integrating sustainability perspective at the company. The second empirical study featured an in-depth semi-structured interview and a workshop session with an engineering research group composed of 4 people, representing engineering design and analysis, material engineering and manufacturing engineering. This study aimed at a better and more detailed understanding of the design process and the main challenges in integrating sustainability perspective at the company.

These two studies were then followed by a case study (Yin, 2009) related to the development of an innovative structural component for a new engine family. The case describes a situation where engineers and designers are faced with the problem of deliberating on the technology for this component representing the best short- and long-term investment for the company, under increasingly stringent environmental legislations. In the specific case, two alternative

candidate manufacturing processes were compared displaying different performance from a sustainability perspective. One process relied on chemical processing whereas the other relied mainly on a mechanical machining technique. Empirical and qualitative data have been collected through the authors' active participation in multi-day physical workshops. In addition, data have been gathered through company and branch-specific documents. Researchers participated in conducting an EIA assessment and developed further the assessment tool, Strategic Sustainability Assessment, at the company to identify the sustainability hotspots. In addition, the new SAVE method was developed, implemented and verified in the case study to clarify the potential sustainability consequences for a new product technology, as well as to assess alternative solution strategies based on the hotspot. From that a design team of five people with different roles: a procurer, a material technology expert, a design leader, a product developer and material expert, and an environmental engineer facilitated by the researchers, developed the resulting scenarios.

Reflective learning has been aided by the continuous participation in regular debriefing activities, which have taken the form of bi-weekly virtual meetings. The findings have been iteratively discussed and validated with the company partner. Verification activities have taken the form of a co-located focus group with industrial practitioners. A Likert scale questionnaire was used to gather feedback on the quality of the model, on the soundness of its purpose and on the support it is able to give to decisions makers in a preliminary design phase. Dissemination activities have also contributed in validating the generalizability of the approach.

5. Findings from descriptive study

The initial explorative study, conducted in collaboration with six large manufacturing companies, brought to the identification of several key factors (categorized into: organization, processes, roles, and tools) needed to implement sustainability in product development. Overall, this exploration activity showed that many off-the-shelves support methods for sustainability assessment are too generic for the companies to apply in their specific context. Others fell short in terms of satisfying the need of the practitioners, something that was also highlighted by Hale (1996), either because too complicated, too theoretical, too expensive or too time demanding to be easily applicable. A common strategy for companies is therefore to develop their own tools instead of using off-the-shelves solutions.

The first of the two empirical studies, featuring a questionnaire survey shared among 35 engineers and product developers, highlighted that individuals feel the responsibility to bring in sustainability aspects and work with value-driven innovation in the product development process. The study showed that it is important to educate staff and discuss the concepts within the company to create clarity on issues of sustainability and value-driven innovation. It is also considered important for the future that each employee contributes to these areas in their daily work, as it is believed that these areas will increase in importance. The result showed further on that there is a need to complement the processes, methods and tools in both areas to provide support for new requirements in the future. For example, it is shown that there is a lack of applicable tools to evaluate alternative solutions and improvements from a customer value and sustainability perspective.

The second of the two empirical studies showed that a major input for sustainability assessments at the company is the REACH (Registration, Evaluation, Authorisation and restriction of CHemicals) candidate list (European Commission 2006), which addresses the chemical substances' potential impacts on both human health and the environment. While REACH is part of today's legislation, severe challenges remain in assessing risks and costs of investing in a given design concept if conditions (e.g., chemical laws, customer requirements, waste costs etc.) will change in future. This problem was well exemplified by one of the respondents in the company research group, who described the current problems with engine components built in the 70s and 80s featuring an extensive use of a material that is now listed in the REACH candidate list. After more than 30 years, this choice is generating high repair costs for engines, since all components featuring this material have to be replaced with other materials. When these engines are provided through total-offer contracts, which means that the manufacturer takes care of maintenance and repair costs, profitability is strongly affected (Isaksson et al., 2009). The company research group stated that being more sustainable is for the company a way to mitigate unforeseen risks in a long-term perspective, but today there is no ability in the concept selection stage to account for change over time when it comes to sustainability matters. Hence, a need for improvement emerged during the interview: *How to assess and visualize in a structured way the risk and the consequences of sustainability-related choices?*

Further on the company research group highlighted that the design concept selection activities need more fact-based evidence to fully consider sustainability issues into the picture. As highlighted by one of the company researchers:

"If you do not have a trade factor between two things, then it is my experience that where you have a number on, it wins... If we cannot set a quantitative measurement for something during conceptual design, it sinks down. When we talk about qualitative measurements there is a tendency to ignore them." (Company researcher in product engineering)

The company research group discussed an option to have some sustainability criteria that can be directly benchmarked with more classical requirements, such as safety, cost, strength and weight. Further on it was discussed to link sustainability assessment results to key performance indicators (KPIs), mainly in terms of ability to: i) increase company revenues: mainly due to the appeal of "green products" and of a more sustainable brand; ii) increase employee productivity: reducing absenteeism, voluntary turnover, commuting, business travels, increasing engagement by means of a better working environment, improved support tools and collaboration among employees; iii) reduce material and water expenses: which can be reached by implementing reuse and recycling strategy on site, emphasizing product take-back and dematerialization.

Findings from the second empirical study was also that the engineering team highlighted a preference towards adding a consequence assessment "capability" to existing sustainability assessment tools, to conduct a WHAT-IF analysis on realistic TO-BE scenario, before design concepts are selected and fully described. This shall be a rather fast assessment step and shall take only a couple of hours compared to conducting a full LCA that can take months. In order to fulfill such request, the authors proposed a method, called Sustainability Assessment and Value Evaluation (SAVE).

6. Findings from the prescriptive study: the SAVE method

The Sustainability Assessment and Value Evaluation (SAVE) was developed through a case study. In this case study two alternative candidate manufacturing processes were compared displaying different performance from a sustainability perspective. In the Sustainability Assessment and Value Evaluation (SAVE) method, the existing EIA tools at the company were expanded with Strategic Sustainability Assessment (SSA) and Net Present Value (NPV) to quantify the consequences of sustainability-oriented design choices. In SAVE, EIA and SSA are used to identify sustainability hotspots and clarify potential sustainability consequences of these hotspots, while NPV is later used to assess alternative solution strategies based on sustainability consequences, as shown in Figure 1.

Figure 1: The SAVE method steps.

6.1. Environmental Impact Assessment

The Environmental Impact Assessment (EIA) is the first level of assessment in the SAVE-method: its objective is to uncover environmental concerns (hotspots) of serious impact potentials along the entire life cycle of alternative design concepts (i.e. from raw material extraction to the disposal phase). EIA is based on a simplified and qualitative life cycle assessment developed in a Swedish industrial consortium, Verkstadsindustrier (HRM/Ritline et al., 2000). Its first step concerns the identification of roles (and individuals) composing the team of experts (e.g. environmental engineer, material expert, product developer, procurer, and, production engineer), as well as the definition of the studied system, and of the available data sources (such as legal, internal/external environmental requirements, technical requirements). Then, the leader of the EIA and SSA so called the SAVE-facilitator, carries

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 (3) - like a maximum level of emissions of carbon dioxide.
- Interested parties: from no negative effect on the company’s environmental reputation (1) to severe damage to the company’s reputation regarding the general public (3).
- Improvement potential: from good and quick improvement (1) to little/no possibilities for improvement (3).

The rating is based on the experience and competences of the SAVE-facilitator. The suggested rating results of the criteria, done independently by the SAVE-facilitator, are discussed with the design team and changed if needed until consensus has been reached within the team. The rating process results in a list of hotspots for the considered life cycle. For those hotspots that have a short-term perspective, the team suggests immediate corrective actions, while those that have a long-term perspective and/or that may be main sustainability issues in future are further analyzed in the SSA step.

6.2. Strategic Sustainability Assessment

The Strategic Sustainability Assessment (SSA), which covers all the three pillars of sustainability (social, environmental and economical) (Kajikawa, 2008), aims to reveal the hotspot complexity and to clarify its short- and long-term sustainability consequences. SSA is based on guiding questions that are founded on backcasting from sustainability principles and a product life cycle (i.e. from raw material extraction to the disposal phase). 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 (Dreborg, 1996). The Sustainability Principles (SP) at the basis of the backcasting exercise 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 2000).

The development of these questions is inspired from a Method for Sustainable Product Development (MSPD) (Byggeth et. al., 2007). See Table 1 for the theoretical base for the development of the guiding questions and Appendix A for a full set of guiding sustainability questions for the case company.

Table 1. Theoretical base for the development of the guiding questions. SP1-3: ecological sustainability principles and SP4: social sustainability principle according Robèrt (2000).

Requirements and risk perspective	Ecological perspective SP1-3	Social perspective SP4	Economical perspective
Short term	Guiding questions 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			

The first step in the SSA clarifies if and why the hotspot(s) is or will be a sustainability problem. As a first task, the material flow (with potential emissions) and life cycle activities (e.g. waste treatment and rest-product treatment) need to be investigated and further described. The SAVE-facilitator then maps out the life cycle activities and describes qualitatively what happens with the flow of material, emissions, waste, and rest-products for each phase. With support from information and data in the value-chain the SAVE-facilitator also clarifies if and how the hotspot occurs, and if and how it can be avoided.

The second step aims to clarify the sustainability consequences that would likely emerge in both a short- and long-term perspective. The SAVE-facilitator selects some guided questions that are related to the hotspot identified and that needed to be further assessed in the SSA, to clarify how and what consequences that can occur, and makes a list of reasons that clearly describe the consequences. The result of the SSA is a summary of reasons that are based on answers to the selected guided questions.

6.3. NPV analysis for alternative solution options in alternative future scenarios

EIA and SSA clarify the nature of sustainability hotspots and the SAVE-facilitator will recommend the design team to suggest alternative solutions to the design. Still, the EIA and SSA do not provide the necessary quantitative clarification of sustainability consequences to provide the design team with a solid base for decision. For this reason, a NPV model is developed to make more explicit the value creation opportunity of adopting a more sustainable solution, under changing future scenarios. The NPV model takes as input the result of the SSA investigation and the company's historical data (e.g., process models, technical documentations and market forecasts) and is governed by six main parameters. Decision makers, by controlling such parameters, can simulate alternative future scenarios, and this is believed to better orient decisions in an early phase (Cluzel et al. 2014). Three of these parameters are derived from the KPI areas highlighted during the empirical study, and are: Waste management costs, Environmental consciousness and Environmental requirements impact.

Waste management is intended to model the likeliness that the costs for disposing of waste and consumables will increase during a future suggested time-period. This parameter will affect the total cost of a product or technology, due to the need for special waste treatment, to the risks that the waste will pollute or contaminate, and to health aspects problems among the

company workers. Environmental consciousness reflects the overall customers' attitude towards buying products that do not meet sustainability requisites. This makes price and volumes to change, because the product is no longer appealing to the potential customers. It also concerns employees and potential employees: bad working conditions are expected to increase the turn-over-rate, exposing the company to the risk of losing core know-how and skills, thus affecting the presented parameter. Environmental requirements impact is a variable that expresses the impact on the product/technology life cycle of the introduction of guidelines, instructions, laws or regulations that constrain the usage of substances consumed or produced by a new product/technology.

A coefficient from 1 to 10 is set by the designers to indicate a weak, medium or strong increase of the above parameters, 1 meaning that the parameter is not subject to any change (e.g., no new environmental requirements will be introduced in the next decade) and 10 meaning extreme changes (e.g., every year new and more stringent requirements will be introduced).

The other 3 parameters relate to: Number of suppliers, Likelihood of a ban on the process and Discount rate. A growing number of suppliers is likely to push down the price of, for instance, consumables and support services. If their number decreases, costs will rise and the profitability of the manufacturing process will be reduced. The Likelihood of a ban on the process is modeled as a TRUE/FALSE condition, and expresses the possibility that a particular solution (material, production process, technology, working procedure) will be banned within the relevant time frame of the project. Discount rate accounts for variations in the discount rate and allows designers to calculate the NPV under different conditions.

By playing with the above variables, decision makers can quantify the cash flows linked to different design concepts in alternative future scenarios, observing where the strongest drivers for implementing sustainability-oriented measures come from. For instance, "waste management costs" might not have a strong impact on the NPV results in the different scenarios, because it is absorbed throughout the process. "Environmental requirements" might have a much more severe impact, due to the likelihood that upcoming stringent regulation will make manufacturing costs skyrocket.

7. Application of SAVE in the selection of an aero-engine component technology

The SAVE-method was implemented and verified in a case study defined in collaboration with the aero-engine sub-system manufacturer (the same company as in the empirical studies). It describes a design situation where the design team is requested to take early-stage decisions on the architecture of a new high-temperature aero-engine component. Engineers and designers are faced with the problem of deliberating on the product technology representing the best short- and long-term investment for the company.

7.1. Environmental Impact Assessment

The engine component was assessed for its full life cycle, i.e. from raw material extraction to the disposal phase, through an EIA. The analysis resulted in two sustainability hotspots; a non-destructive testing using hazardous substances and a manufacturing process generating hazardous substances. The manufacturing process, that is the Electro-Chemical Milling (ECM), was further spotlighted as the most critical one as alternative substances could be

found for the non-destructive testing. However, the use of ECM was one of the most effective design options as production technology, as it in this case was cost-and time efficient, and did not require post-treatments of design surface. Therefore, statements that ECM processes generate hexavalent chromium, nickel, and lead particles when applied for nickel-based alloys needed to be further investigated. In this particular case the engine required a nickel-based alloy to fulfill the technical requirements and it could not be replaced by another material. In addition, concerns were raised about an upcoming environmental requirement on hexavalent chromium that would generate extra costs and reduce efficiency of the production line. Rumors of an upcoming ban on the ECM process further suggested to the design team that the ability to benefit from a long-term investment in the proposed option needed to be understood more in detail.

7.2. Strategic Sustainability Assessment

The SSA assessment was conducted in several steps. Firstly, the material flow, potential emissions, waste treatment and rest-product treatment were investigated to clarify why the ECM process generated hexavalent chromium, nickel, and lead particles when applied for nickel-based alloys. The investigation was conducted mainly through a literature review and through meetings with potential suppliers of the ECM process. The investigation focused on the opportunity to avoid the emission of toxic substances and pollutants, as well as on the possibility to keep such emissions isolated and in closed technical loops. The list of guided questions used to clarify short- and long-term sustainability consequences is shown in Appendix A. Most answers for the short-term perspective related to present environmental, social and economical requirements, such as documented requirements stated by the company, customers, and in legislation. The answers from a long-term perspective included reflections and logical reasoning on the consequences of the ECM implementation. From an economical short-term perspective the choice of ECM was shown to be beneficial, as some investments had already been made and some work had already been performed in terms of investigation of suitable suppliers. From the socio-and ecological perspective, the risk of leakage and the effect on the company image if this leakage would happen needed to be considered more in depth.

More in detail, the SSA resulted in the following list of reasons for not investing in ECM:

- i. the use of carcinogenic and allergenic substances could be justified from a social perspective if there are alternatives to use;
- ii. according to the precautionary principle alternatives should be chosen when there are environmental- and health risks;
- iii. material lists showed a warning for a ban of processes that involve Cr VI;
- iv. the company might not take economic advantage of an investment in ECM, due to the introduction of new severe requirements and an upcoming ban;
- v. only a few sub-contractors might be able to provide support to the process in the long run;
- vi. the costly investment in new tools was not justifiable for a process that is not very developable.

The final recommendation from the SSA was to ask the design team to suggest an alternative manufacturing process. The proposed option from the design team was the Mechanical Milling (MM) process. It was presented as an alternative to the ECM process although it is more expensive to run. However, it involves only one hazardous substance (nickel) and

produces less toxic material compared to the ECM process. Therefore the MM was not considered as a hotspot that needed further investigation after the EIA. To visualize and even better understand the consequences from a value perspective alternative future scenarios were defined and benchmarked using a NPV calculation.

7.3. Scenario definition in the NPV analysis

The definition of future scenarios in the NPV calculation is supported by the process shown in Figure 2. In the studied case, the process was guided by the SAVE-facilitator, who was in charge of gathering relevant information to develop and populate the NPV model, and of facilitating discussion among the design stakeholders. The design team was multidisciplinary and composed of five people, namely: a procurer, a material technology expert, a design leader, a product developer and material expert, and an environmental engineer. The team has initially verified the links between the six governing parameters and relevant factors in the value model. The members in the design team also gave their best estimate of the value for the selected parameters, and expressed their level of confidence in each answer they gave. See Appendix B for answers in relation to the most likely future scenario for ECM and MM. The answers were gathered and three alternative NPV calculations were generated in the model for three different scenarios: i) scenario based on the As-Is context/situation; ii) scenario based on the assessment from most confident stakeholder in the design team; iii) average assessment from the entire team. The results were presented to the design team to facilitate discussion and agreement on the correct scenario, and thereby on the best solution from a sustainability and value perspective.

Figure 2: Scenario definition process involving a SAVE-facilitator and a design team.

The governing parameters were linked to the NPV model on the basis of series of assumptions. Firstly, the ECM process is the one most exposed towards the introduction of new environmental requirements, while perturbations on MM operations can be almost neglected. For ECM, new requirements mean introducing more complex instruments and machineries in the process, which are in general more expensive to purchase and to use. Also, setups might require more time (as the procedure is more complex), upgrades might need to be implemented more frequently (hence reducing the availability of the production line), and more specialized manpower is needed to manage a more complex/controlled process

triggered by more stringent requirements. The latter is expected to generate higher costs for the company, because the necessary competencies to deal with a more complex process might be difficult to find, and individuals do likely require more training. New requirements might also be introduced to regulate the activities in the working environment, to ensure safety of the individuals involved in the process.

Secondly, customer environmental consciousness does mainly affect the use of the ECM process and indicates the likeliness that the OEM (the customer) choses another supplier because of the company not fulfilling internal requirements for suppliers selection, hence reducing setting volumes for ECM-manufactured components.

Furthermore, waste management costs are affected by new norms and legislations too, as toxic and hazardous materials might require more complex and expensive procedures to be properly handled, and this has a direct impact on the profitability of the manufacturing line. In addition, business partners might be discouraged to supply consumables and spare parts to keep the ECM process up and running if the legislation becomes more stringent. Fewer suppliers would mean higher purchase prices and lower flexibility.

Eventually, a ban on the ECM process will have severe negative consequences with regards to costs related to the dismissal of the ECM manufacturing line, its conversion in MM, the disposal of its waste, the reduced line availability during the conversion, and the training costs generated by the change in production process. In general, it is beneficial for the manufacturer if the ban is introduced as late as possible. To make an extreme example, if the ban is introduced just after the ECM manufacturing line has been implemented, the company will not be able to gain back any of the investment costs. Hence, the model considers the year in which the ban is introduced as an important variable to calculate the NPV. It is assumed that, if the ban is introduced at year n , at $n+1$ the company will move back to MM (i.e., to its profitability curve). However, the MM process will likely be less efficient when introduced at year $n+1$ compared to a situation in which it is introduced at year 1. A penalty is introduced in the model to render such a loss of performance, which is due by the lack of lessons learned generated between year 1 and $n+1$. The NPV calculation considers a time span of 10 years (2013-2022), after which the machines used in the process are considered to have achieved the end of their life. The NPV is calculated in Euros and for simplicity purposes the discount rate is kept equal to 8% for all 3 scenarios presented. (Please note that the data used as input in the calculation sheet have been scaled and used for illustrative purposes only.) Three scenarios are considered in the calculation. These are characterized by different values of the parameters presented in section 7.3. See Table 2 for an overview.

Table 2. Scenario summary from the SAVE-method.

<i>Parameters used in the NPV</i>	<i>Scenario 1 (static)</i>	<i>Scenario 2 (answers from the most confident individuals in the design team)</i>	<i>Scenario 3 (weighted average)</i>
<i>Environmental requirements impact</i>	1	10	6
<i>Waste management costs</i>	1	10	7
<i>Customer environmental consciousness</i>	1	6	3
<i>Number of ECM</i>	3	3	3

<i>suppliers in 10 years</i>			
<i>Ban on ECM process</i>	NO	YES	NO
<i>Year (of ban introduction)</i>	N/A	2019 (year 6)	N/A
<i>Discount rate</i>	8%	8%	8%

7.4. Scenario 1 results: As-Is context/situation

The first example considers a static scenario, where very small changes in the existing regulations are foreseen within the next decade, and where the ECM process is not going to be banned. This scenario considers new environmental requirements to be updated and introduced at a very slow pace in the next 10 years. Also, it considers waste management costs to remain stable and similar to the ones experienced today. Customers are considered not to be particularly environmentally conscious, and final users are not influential enough to orient the engine and aircraft manufacturers purchasing choice. Eventually, scenario 1 foresees the same number of companies (3) operating in the market at the end of the 10 years period, and the market is able to provide support to the ECM process. In this scenario customers value performances more than sustainability, and under these assumptions ECM-manufactured products are more profitable than their MM counterpart throughout the entire decade (Figure 3). The ECM process renders a higher cumulative NPV after 10 years, and the break-even point is reached at year 6, about 1 year before MM. If the societal consequences (company image, risk for accidents, etc.) are minor, the design team is likely to orient its choice towards this first option.

Figure 3: Scenario 1 results – from As-Is data

7.5. Scenario 2 results: assessment from the most confident individuals in the design team

This scenario is built considering the answers to the questionnaire characterized by very good or good confidence of the individuals in the design team. It considers: the introduction of a ban for the ECM process starting from year 5; a very quick increase in the introduction of

new environmental requirements; a quick increase in waste management costs; a slow increase of environmental conscious customers; and, only 4 suppliers available at the end of the decade.

Figure 4 shows that the profitability of ECM-manufactured products decreases year after year, in line with the introduction of new legislations. The NPV curve is flatter than in the example above to reflect the higher costs for equipment, labour, consumables, and waste treatment, as well as the diminishing appeal of ECM-manufactured products. The investments needed at year 5 to convert the manufacturing line from electro-chemical to mechanical strongly impact cash flows and the expected NPV. From year 6 onwards the actualized cash flows curve for ECM follows the MM one. In such a scenario, ECM is of economical disadvantage in the long-time perspective; hence MM is preferred from the start.

Figure 4: Scenario 2 results- from most confident in the design team

7.6. Scenario 3 results: weighted average assessment from the entire team

This scenario builds on a weighted average of the values given by the questionnaire respondents (see: Appendix 2), which also considers the overall confidence in the answers. All answers have been weighted the same, and the result has been approximated to the closest integer. This scenario considers the ECM process not to be banned at least within the next decade. However, it foresees significant changes in the way environmental requirements are introduced in the industry, together with a steady increase in waste management costs and in the number of environmentally conscious customers.

From year 4 onwards, the combined effect of waste management costs, new environmental requirements and better consciousness about the environment, together with the reduced competition among the suppliers, strongly impacts ECM profitability (see Figure 5). The actualized NPV for ECM progressively reaches break-even at the end of year 10, while MM reaches it between year 7 and 8. As a result, the company is likely to orient its choice to MM.

Figure 5: Scenario 3 results - weighted average assessment from the entire team

The results from the three different scenarios were discussed with the stakeholder team and a consensus and agreement was reached with the second scenario being the most likely alternative to happen in this case. Thereby the best manufacturing process from a sustainability and value perspective could be chosen, in this case the MM.

8. Verification

The approach and its constituting models have been verified with designers and process owners in co-located industrial workshops. A Likert scale questionnaire (using a scale from 1-9, with 1= strongly disagree, 5= undecided and 9= strongly agree) has been used to gather feedback on the quality of the model, on the soundness of its purpose and on the support it is intended to give to decisions makers in a preliminary design phase.

The design team involved in the analysis has expressed a positive feeling (average score of 6.6/9, standard deviation of 0.8) in term of the relevancy of the results obtained by the SAVE method in general and on the NPV analysis in particular. The method is acknowledged to provide a clearer picture of the design decision to be taken, if compared with the current practices. A similar result (average score of 6.6/9, standard deviation of 1.26) has been obtained in terms of the team perception related to the capability of the tool to enable faster and better decisions. The method is valued for its synthesis capabilities and for its ability to visualize a complex decision situation by simple means. The stakeholders also appreciated the role of the method as boundary object, which is when it enables the team to share information and establish a dialogue across disciplines (Carlile, 2002). The team is mostly undecided (average score of 5/9, standard deviation of 1.02), although opinions differ, when it comes to the ability of the tool to eventually diminish the total amount of analyses needed to support preliminary design decisions. The standard deviation value also indicates that team perception on the above topics is relatively homogeneous.

9. Discussion

Other similar methods and alternatives to LCA have been developed previously, such as an integrated Quality Function Deployment for Environment (QFDE) approach that considers cost, quality and environmental parameters to identify improvement strategies for sustainable product development (Berejetli and Genevois, 2013). There are some common characteristics with this approach and our proposed SAVE-method, given some advantages in comparison to LCA, such as: aim to be a support in the early phases of product development; consider both environmental and cost issue; and, provide the user with a quantitative result. However, in contrast to the QFDE-based approach and a LCA, the SAVE method combines a forecasting and backcasting approach, provides transparency when including a qualitative socio-ecological assessment, and, uses scenario building to facilitate decisions for the product development team.

The main uniqueness and novelty of the SAVE method lie in effects it wants to trigger in the design team, which are to:

- *make sustainability consequences more concrete and understandable during design concept selection activities rather than to have an exact measurement;*
- *simplify and prioritize, systematically asking what is important in the sustainability assessment, rather than to reduce the sustainability problem.*

The first one is achieved by adding the NPV calculation to the qualitative assessment. The method allows undertaking the sustainability assessment in a more structured way than what happens today in preliminary design, through scenario building based on socio-ecological assessments, including back-casting to cover the longer time perspective. Still, varying the calculation is more important than the actual figures, and the focus is on assessing and comparing alternatives primarily. Partially this is due to the imprecision of data, and partially to highlight the sensitivity and resilience of candidate alternatives and scenarios. The NPV results should be seen as a “common denominator” for the different members in the team to confront each other on sustainability matters, especially when opinions differ. Also, they shall suggest the team to avoid looking only at a static scenario, but rather to grow an understanding among a range of possible scenarios. The most correct or realistic one is likely to emerge from a dialogue between the stakeholders, and supporting this dialogue is the main purpose of SAVE.

The second one concerns the observation that engineers trust numbers when taking decisions. Still, the adoption of a simulation approach may become counterproductive, as it disguises the complicated nature of sustainability problems. However, following the steps in SAVE guides the design team in making explicit the assumptions, restraints, and statements rather than allowing them to remain implicitly inherent in high-level statements. This is because decision makers need to treat sustainability at a level comparable with other design parameters, which are in general more technical and more established, and hence prioritized when making decisions. The SAVE method supports the transition from qualitative to quantitative, while keeping data and information available to users. In a sense, the method is more transparent than LCA (where the team insert data in a computer and get figures). If the team does not understand why certain parameters are chosen in the NPV model, they can go back to SSA to understand the rationale through qualitative and descriptive results. In this way the quality and completeness of data and assumptions can be systematically improved, i.e. moving from opinions and intuitions to evidence-based statements.

The proposed SAVE-method was also validated through a case study which indicated that the method is applicable, possible to implement and gives enough support for decision-making including sustainability- and value perspective. The case study illustrated how EIA and SSA identified sustainability hotspots and clarified potential sustainability consequences for a new product technology, and how NPV was used to assess alternative solution strategies based on the hotspot. The results from the three different scenarios were discussed with the design team and a consensus and agreement was reached about the second scenario being the most likely alternative to happen in this case. Thereby the best manufacturing process from a sustainability and value perspective could be chosen, in this case the MM. A weakness of the verification part has been the time limitations of the company experts to explore the suggested approach in depth.

In future work the model has to be further validated and a sensitivity analysis has to be performed to test the model robustness in the presence of uncertainty. More in-depth studies are also needed to understand how to position the method in the frame of the existing risk assessment methodologies, and to understand how the results of the sustainability-value study have to be balanced with other risks, e.g. destroyed image, increased competitiveness, less energized employees, increased cost, less profit, and more expensive investments. Already, and as presented, feedback from industrialists support the usefulness of the method as is. NPV calculations are common when assessing alternative investments in industry, but including sustainability aspects have previously been difficult. From an industrial adoption perspective it is attractive to make use of the NPV calculations also to include sustainability aspects, and the SAVE method has demonstrated this ability.

To fully understand sustainability consequences, a long-term perspective is needed (Lozano, 2008). This is however not normally considered in the support tools, such as LCA, used today by product development teams. In addition the proposed SAVE method raises awareness of sustainability risks for the business. This has shown to be an incentive to identify new technological and organizational innovation opportunities (Gaziulusoy et al., 2013). According to the World Business Council for Sustainable Development (2004), risks related to sustainability are considered to have a significant impact on businesses. If the company understands how design actions are connected to the company strategy, and puts them in the context of a vision for a sustainable society, a proactive behavior to address sustainability issues can be encouraged (Boyle, 2004).

10. Conclusions

The proposed Sustainability Assessment and Value Evaluation-method (SAVE) links sustainability to its value consequences and strengthen a design team's ability to account for sustainability-and value aspects already in early phases of development. Hence, it successfully addresses the identified lack of effective methods to include sustainability and value aspects in early development situations experience insufficient data about forthcoming designs and their processes. The SAVE-method makes sustainability consequences more concrete and understandable by combining qualitative with quantitative assessments, together with scenario building; and, it supports simplifying and prioritizing by systematically asking what is important in the sustainability analysis, rather than to reduce the sustainability problem. Through a real situation example the method demonstrated its applicability. The logics of first identifying sustainability hotspots and clarifying potential sustainability

consequences for a new product technology, followed by assessment and derivation of quantitative scenarios, which is used by users for exploration and variation, was supported. The method allows undertaking the sustainability assessment in a more structured way than what is done today in preliminary design, through scenario building based on socio-ecological assessments, including backcasting to cover the longer time perspective. In addition the result of SAVE provided design teams a means to display their value dimensions in Net Present Value terms, on an equal basis with other decision support results. In future work further validations are needed and the robustness and sensitivity of the model need to be further assessed.

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Highlights

- The SAVE-method enables value assessment of sustainability issues.
- The method combines qualitative with quantitative analysis.
- An industrial project team verified the application of the method.

Biography

Sophie Hallstedt holds a Ph.D. Degree in Mechanical Engineering with emphasis on Sustainable Product Innovation from Blekinge Institute of Technology, Karlskrona, Sweden. She leads a research track with focus on Sustainability Integration in Conceptual Design. She has industrial experience from the steel industry, biological monitoring area and aero industry. Her work and research interest concerns how a strategic sustainability perspective can be integrated and implemented into product innovation process with focus on the early phases.

Marco Bertoni is associate professor at Blekinge Institute of Technology, with competence in Product Innovation, Value Driven Design and Engineering Knowledge Management matured within EU FP6 and FP7 projects in the aerospace domain. His research interest lies in the conceptual development phase of complex products and services. The objective is to understand how knowledge from the later phases of a system lifecycle can be made available in preliminary design to support decision-making activities.

Ola Isaksson is senior company specialist in product development at GKN aerospace engine systems in Sweden. He is also an Associate Professor and Adjunct Professor in Product and Production Development at Chalmers University of Technology. His work and research interest concerns the improvement of practices for product development, including knowledge engineering, product service systems development, design automation and innovation.

Appendix A: Battery of generic guiding questions to use in the Strategic Sustainability Assessment

Requirements and risk perspective	Ecological perspective SP1-3	Social perspective SP4	Economical perspective
<p>Short term (1-10years) for any life cycle phase:</p> <ul style="list-style-type: none"> • Source material extraction/production • product production • usage & maintenance • end-of life 	<ul style="list-style-type: none"> • Are any metals or alloys used that have any indications for restrictions (see material lists)? • Are any substances used that have any indications for restrictions in today's requirements (steering and informative documents SIN-list) or legislation, (e.g. REACH)? • Could emissions and waste substances included in the REACH-candidate list be eliminated? • Do the activities result in physical damage to Nature (for example due to mining of large areas, moved water sources, replaced harvesting areas or destroyed forests for buildings and roads)? • Are there scrap and/or emissions of metals/alloys and in that case is it possible to eliminate these? • Could the fossil-based emissions be reduced during the life cycle phases? • Could other emissions be reduced during the life cycle phases? • Could the amount of clean water usage be eliminated? • Could the amount of waste and spill be reduced? • Will the proposed solution result in a lighter (less weight of final product) solution? • Is the proposed solution designed for remanufacturing and/or recycling? • Could the noise during the usage and maintenance of the product be reduced? 	<ul style="list-style-type: none"> • In the daily work, is the working environment safe today? • What is the likely consequence if an accident happens? • What is the risk in the near future (1-10 years) with the proposed solution to have: <ul style="list-style-type: none"> - accidents that result in injuries - leakages that result in negative human health - occupational diseases, - lost days and absenteeism, - work-related fatalities? • Is there a dependency of conflict materials for product components and/or its production (see material lists)? • Are the laws and regulations followed in the country: that extract the raw materials or produce the chemicals used in the company's product/production; and/or that conduct maintenance; and/or that conduct disassembly and recycling? • Are there any risk for unsafe transports of materials, substances and products? 	<p>Are there any economical advantages or disadvantages today for investing in this proposed solution (product, process or Product Service System)?</p>

<p>Long term (10-20+ years) for any life cycle phase:</p> <ul style="list-style-type: none"> • Source material extraction/production • product production • usage & maintenance • end-of life 	<ul style="list-style-type: none"> • Is there a dependency of metals or alloys used in the proposed solution that has restrictions, see material lists? • Will it be possible to substitute substances that have restrictions in steering and informative documents, such as the SIN-list? • Could Nature recover due to activities such as mining of large areas, moved water sources, replaced harvesting areas or destroyed forests for buildings and roads? • Will there be an accumulation of metals or valuable materials in any of the life cycle phases? • Is it possible to keep hazardous substances in closed technical loops over time? • Could emissions and waste substances included in the SIN-candidate list be eliminated? • How will the proposed solution eliminate emissions and/or scrap of metals/alloys? • How could the proposed solution support CO2-neutral facilities and at same time reduce emissions in all life cycle phases? • How could other emissions be eliminated during the life cycle phases? • How could the proposed solution support substitution to renewable fuels in all life cycle phases? • How is the proposed solution designed for an optimized material and energy perspective, for example how is the materials/components returned to the value chain for remanufacturing and/or recycling? 	<ul style="list-style-type: none"> • Will the proposed solution cause violation of human needs as described in the categories of ISO 26000? • Will the proposed solution cause no violation of the ten principles of the United Nations Global Compact? • Is there no risk ever, related to the proposed solution, for unhealthy and unsecure working environment that results in: <ul style="list-style-type: none"> - accidents that result in injuries - leakages that result in negative human health - occupational diseases - lost days and absenteeism - work-related fatalities? • Is there a risk that there will be stricter regulations and requirements in the working environment area for example regarding hazardous substances? • How to ensure efficient and safe transports of materials, substance and products related to the proposed solution? 	<p>Are there any advantages or disadvantages for investing in this manufacturing process in future?</p> <p>Are there any risks that there will be stricter regulations and requirements regarding emissions and waste, usage of materials and alloys, substances, and/or treatment of waste and scrap, that will result in new investments or added costs for the company?</p>
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Appendix B: Stakeholder answers in relation to the most likely future scenario for ECM and MM

In order to tune the parameters in the NPV calculation, a questionnaire was shared to gather information from the design team about future scenarios. The questionnaire was composed of 7 main questions, as shown in Table below. The respondents were asked to express their position using a scale from 1 to 10, where 1 indicates minimum risk, and 10 a very high risk. Also they were asked to express their level of confidence in the data provided, using a 5 step scale (from “very bad” to “very good”). In total, 5 questionnaires have been answered concerning ECM, while only 4 concerning MM.

	Level of confidence in the answer				
11.					
(1= smallest risk, 10= highest risk)	Very good	Good	Unsure	Bad	Very Bad
“What is the risk that environmental regulations will become more severe in a 10-year time?”	12.	10, 10	1.5	2	13.
“What is the risk that the company will experience increasing waste management costs when using ECM?”	14.	10,10	7,3	15.	16.
“What is the risk that the company will experience increasing waste management costs when using MM?”	10	2	2, 2	17.	18.
“What is the risk that the company will not be chosen as supplier because customers recognize the environmental problems related to ECM?”		6.5	5, 3, 1	1	19.
“What is the risk that the company will not be chosen as supplier because customers recognize the environmental problems related to MM?”	1	1, 1	1	20.	21.
“Is there any risk that ECM will be banned as a production process in the future?”	22.	In 1-5 years	In 1-5 years, In 1-5 years, In 6-10 years	No risk	23.
“Is there any risk that MM will be banned as a production process in the future?”	No risk, No risk	No risk, No risk	24.	25.	26.
“How many suppliers do exist for ECM nowadays?”	27.	2, 2 or 3	2 or more,	1	5