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INTRODUCTORY PROCEDURE FOR SUSTAINABILITY-DRIVEN DESIGN OPTIMIZATION

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ABSTRACT
In response to the increasingly competitive global market, there is a growing interest in design optimization. Being able to include aspects of socio-ecological sustainability in product design should aid companies to both improve current competitiveness and to identify viable long-term investment paths and new business opportunities in the evolving sustainability-driven market.
A case study of a water jet cutting machine is used to illustrate a new iterative optimization procedure that combines a technical assessment with a sustainability assessment. Sustainability assessment methods/tools are first used to identify prominent sustainability problems from present-day flows and practices ("societal indicators") and to generate ideas of long-term solutions and visions. Based on this, preliminary ideas about likely desirable changes in machine properties are obtained. Technical investigations are then performed to assess if/how these particularly desirable changes in machine properties could in principle be realized through changes in design variables. After that, obtainable changes are fed back to a new and more refined sustainability assessment to find out the societal implications of these changes. This may in turn result in other desirable design changes, which may call for a new and more refined technical assessment, etcetera.
The experience from the case study indicates that the suggested integrated and iterative working procedure should be able to add information about socio-ecological impacts of product properties and influence design criteria used in prioritisation situations during product development.

Key words: product development, optimization, sustainability assessment, simulation, water jet cutting

1. INTRODUCTION
Product innovation is a particularly critical intervention point for the transformation of society towards sustainability. Overuse of resources and socio-ecological impacts of production, distribution, use and disposal are evidence that current methods of decision making during product innovation are insufficient. In many cases, the majority of a product's socio-ecological impacts are already committed at the design phase. Being able to include aspects of socio-ecological sustainability in product design should therefore aid companies to improve current competitiveness as well as to identify viable long-term investment paths and new business opportunities in the evolving sustainability-driven market.
Several methods/tools have been proposed to integrate environmental aspects into product development. Some examples are 'cleaner production', 'pollution prevention', 'eco-design', 'design for (the) environment', 'design for recycling', and 'sustainable product development' [1-3]. There is however, a slow progress in the actual "greening" of products. Reasons may include limitations in time and economic resources for an effective application of eco-design methods/tools [4, 5], or there may be a lack of incentives other than the expected environmental benefit [6]. In addition to that, some of today's eco-design tools have a rather vague connection to the social and/or business dimension of sustainable development [7]. Some methods/tools have been developed with the specific aim to bridge this gap. This includes a Method for Sustainable Product Development [8], Strategic Life-Cycle Management [9], Templates for Sustainable Product Development [10], and Systems Modeling within Sustainability Constraints [11, 12].
Assessment of the technical functionality of a design proposal is another important part of product development. This could be done through physical testing or computer simulation. A major advantage of computer simulation is that the number of design proposals that could be tested within a limited frame of time and money can be significantly increased compared to physical testing [13]. Simulations

of some technical aspects of a product are often used to aid product design optimization. A virtual machine, for example, has been used to investigate how particularly desirable changes in machine tool properties could be realized through changes in design variables [14, 15]. Such optimizations have, however, often a relatively narrow focus on technical and to some degree business economic aspects. To avoid sub-optimization, the economic perspective should be better integrated in prioritization decisions. They should also take into account the use phase of the product [16]. And foremost, to our knowledge, there is no commonly used optimization procedure that combines life-cycle parameters from a sustainability assessment with parameters from a technical assessment. Such a combined optimization procedure might provide valuable support for sustainable product development.

This paper provides basic ideas for an iterative optimization procedure that combines a technical assessment with a sustainability assessment. In this way, it might be possible to find win-win-win situations for the company, the customer and society as a whole and thus to avoid some trade-off situations early on. The procedure is introduced through a case study.

2. CASE STUDY - WATER JET CUTTING

2.1 Case Relevance

Water jet cutting is used as a first case study, mainly due to its good basic potential to be an effective and sustainable manufacturing technology. Some advantages are high accuracy and flexibility, low work piece material losses and inert and abundant main processing substances (water and sand). It is also possible to cut in different types of material and material thicknesses. Compared to most other cutting techniques, there is also often a lesser need for post-operations, due to low thermal and mechanical influence on the work piece.

2.2 Water Jet Cutting Technique

Water jet cutting is a manufacturing technique that uses the erosion power of water and sand to shape the work piece. The basic principle is to channel highly pressurised water through a narrow nozzle in the cutting head, concentrating a high amount of energy in a small area and thereby creating the cutting power. Others have described this in more detail [17]. A typical water jet cutting machine design is shown in Figure 1.

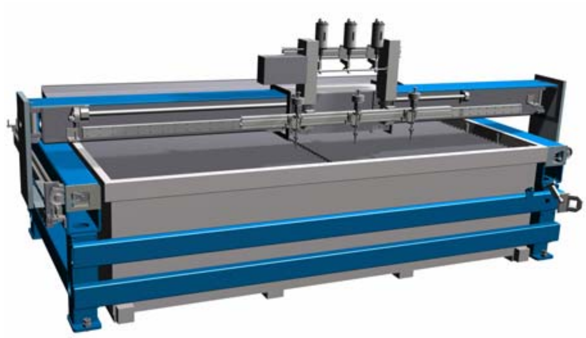

Figure 1. Example of a water jet cutting machine.

2.3 Case Working Procedure

The first step of an integrated assessment is to gain an initial understanding of what conceptual designs to assess and in relation to what product design criteria. Here, the focus is already set on water jet cutting machines – both today and in a sustainable future. The product design was initially focused around technical performance like cutting accuracy and speed but other relevant objectives should be clarified through the iterative integrated assessment.

Successively more and more refined sustainability assessments were carried out using methods/tools like:

- Strategic Life Cycle Management (SLCM) [9] based on the ABCD-procedure for Backcasting from Sustainability Principles [18, 19].
- Templates for Sustainable Product Development (TSPDs) [10].

- Causal Loop Diagrams (CLDs) and resulting Reference Behaviour Patterns (RBPs) [11, 12, 20-22].

In parallel, more and more refined technical assessments were carried out using methods/tools like:

- Intuitive thinking, supported by highly simplified models for which an analytical solution could be found through hand calculations.
- Simulation using more detailed models that call for numerical solutions, for example, the finite element method.
- Multi-disciplinary simulation of the complete system using a "virtual machine" [14, 15].

The two simulation domains mutually influence each other, so there is need for iterations between them (see Figure 3 and 4). Since the main purpose of this paper is to suggest a working procedure, only some illustrative results from the assessment of water jet cutting are presented below.

2.4 Sustainability Assessments of the Water Jet Case

2.4.1 Strategic Life-Cycle Management

SLCM and ABCD are methods/tools for overarching sustainability assessments. An ABCD identifies the main potential sustainability-related problems and principle solutions for a certain company, product or activity. Such an assessment could be upgraded to an SLCM by more systematically integrating a life-cycle overview, including supply-chain, manufacturing, use and reuse, recycling or disposal. Both methods also give suggestions for how to prioritize between potential solutions to the problems. In this study SLCM was used to make an initial overarching strategic action plan of the water jet cutting company and its life-cycle activities. This also gave input to a template for sustainable product development, and other related assessment and communication tools that are described below.

Among other things the SLCM showed that electricity use could be a concern relative to other properties (see B-step in Table 1). This is due to the current generation of the electricity in unsustainable energy systems. This led to recommendations like buying electricity from renewable energy sources, mapping out and reducing energy and material use, etc (see steps C and D in Tables 1 and 2).

2.4.2 Templates for Sustainable Product Development

This is an approach to compile and communicate narrative statements from a sustainability expert on potential sustainability problems/benefits of a studied product concept and related principle solutions [10]. This is to trigger creativity in product development teams, and starting their sustainability assessment from an informed position. The template approach is particularly intended for the early stages of the product innovation process when the design freedom is still large. In this study the template approach was used to clarify product development consequences of the overarching sustainability problems/benefits and principle solutions from the SLCM assessment of the water jet cutting company. The results of the TSPD and SLCM were also later used as input to a Causal Loop Diagram (CLD), giving a systems description of water jet cutting in a sustainability context.

The TSPD added to the sustainability assessment, among other things, a concrete recommendation to focus on reducing the weight of the moving parts in the water jet cutting machine (see template IIC in Table 3) but without reducing its manufacturing accuracy and speed. This would reduce the energy use for water jet cutting activities throughout the machine life-span, which would in turn reduce the impacts of unsustainable energy systems such as climate change. Other ways to reduce energy use were also identified such as improved jet efficiency.

Table 1. Steps B and C of an SLCM assessment. Examples of sustainability problems/benefits in relation to Sustainability Principle 1 (B-step) and action ideas (C-step).

ABCD Assessment Step	Life-Cycle Phases Assembly	Use	Waste management
B **(Current problems/benefits)**			
SP 1	- Use of virgin scarce metals in electronics	- Electricity use for moving parts and water pump	- Use of fossil fuels in waste transportation
SP 2	- …	- …	- …
SP 3	- …	- …	- …
SP 4	- …	- …	- …
C **(Action Ideas)**	- Design for disassembly and recycling - … - … - … - … - …	- Reduce material and energy consumption through improved design - Improve jet efficiency - Map out life-cycle material and energy use -… - …	- More compact machine design would reduce waste generation and trucks could be substituted by railroad transportation … - … -… - …

Table 2. Step D of an SLCM assessment. Examples of how action ideas from the C-step are prioritized and planned.

Actions	Priority (time frame) Very High (yr 1)	High (yr 2-5)	Medium to Low (yr 6+)
- Map out life-cycle material and energy use	>>>>>>		
- Reduce material and energy use through improved design		>>>>>>>>>>>>>>>>>>	
- Design for disassembly and recycling		>>>>>>>>>>>>>>>>>>	
- Improve jet efficiency		>>>>>>>>>>>>>>>>>>	>>>>>>>>>>>>

Table 3. Examples of sustainability problems/benefits and action ideas resulting from TSPDs.

TSPDs for Water Jet Cutting			
I. Market Desires /Needs	**II. Concepts**	**III. Extended Enterprise**	
Current market desires addressed:	**Conceptual design of today's product:**	**Current stakeholder communication /cooperation:**	**B (current problems/benefits)**
… "Water jet is used to cut different materials in high accuracy applications like the automobile and aircraft industries" … … "Waterjet is a resource efficient and relatively safe cutting technology that helps creating a good factory working environment." …	..."water jet cutting uses fossil fuel based electricity and thereby contributes to increasing atmospheric CO2-concentrations" - … - …	… "there is a lack of cooperation ,e.g., for material recycling "… - … - …	
Likely future market desires to address	**Likely conceptual design of future product:**	**Likely future stakeholder communication /cooperation:**	**C (future action ideas)**
… "Cutting speed and accuracy will need to be improved" … - … - …	…"Focus on reduced moving weight" … … "Focus on a self sufficient system with internal recycling of sand and water" … - … - …	…"start strategic cooperation with material recycling companies to improve purity of recycled fractions"… - … - …	

2.4.3 Causal Loop Diagrams and Reference Behavior Patterns

A Causal Loop Diagram (CLD) is a method/tool that aims to clarify the causal structure between variables of a given problem. The variables are connected with positive and negative arrows, which denote that the target variable is either increased or decreased by an increase in the source variable. A Reference Behavior Pattern (RBP) intends to map out potential behavior over time for key variables of the CLD. The system boundaries of a CLD are largely set by the specific question that it should try to answer. This study used an initial CLD that after some iterations was focused on investigating the following question: What are some relations between the water jet cutting life-cycle (and machine performance), its sustainability impacts and customer demand for water jet cutting?

The CLD assessment resulted in a widened perspective on the driving forces behind the sustainability impacts of water jet cutting (Figure 2). It was shown that improved technical performance (e.g. reduced moving weight, increased cutting accuracy and/or increased speed) could have an important role in reducing the energy and material use of the water jet cutting life-cycle. Related sustainability impacts and costs could also be reduced. The CLD assessment also opened up for a later assessment of the socio-ecological consequences of the design changes that were suggested by the technical assessment. More sophisticated technical reasoning was also initiated. For example, it was found that a decreased moving weight might reduce other aspects of machine performance like cutting accuracy and speed. Reduced accuracy could lead to an increased need for post-operations that, in turn, could increase the energy demand of the whole manufacturing process and also add other negative side-effects from a larger sustainability perspective. Moreover, if a high cutting speed is not maintained the water consumption might increase, which is negative from a sustainability perspective. Because of these possible relationships between lightness, accuracy and speed, a minimum requirement for accuracy and speed was set before the optimization study. (see below)

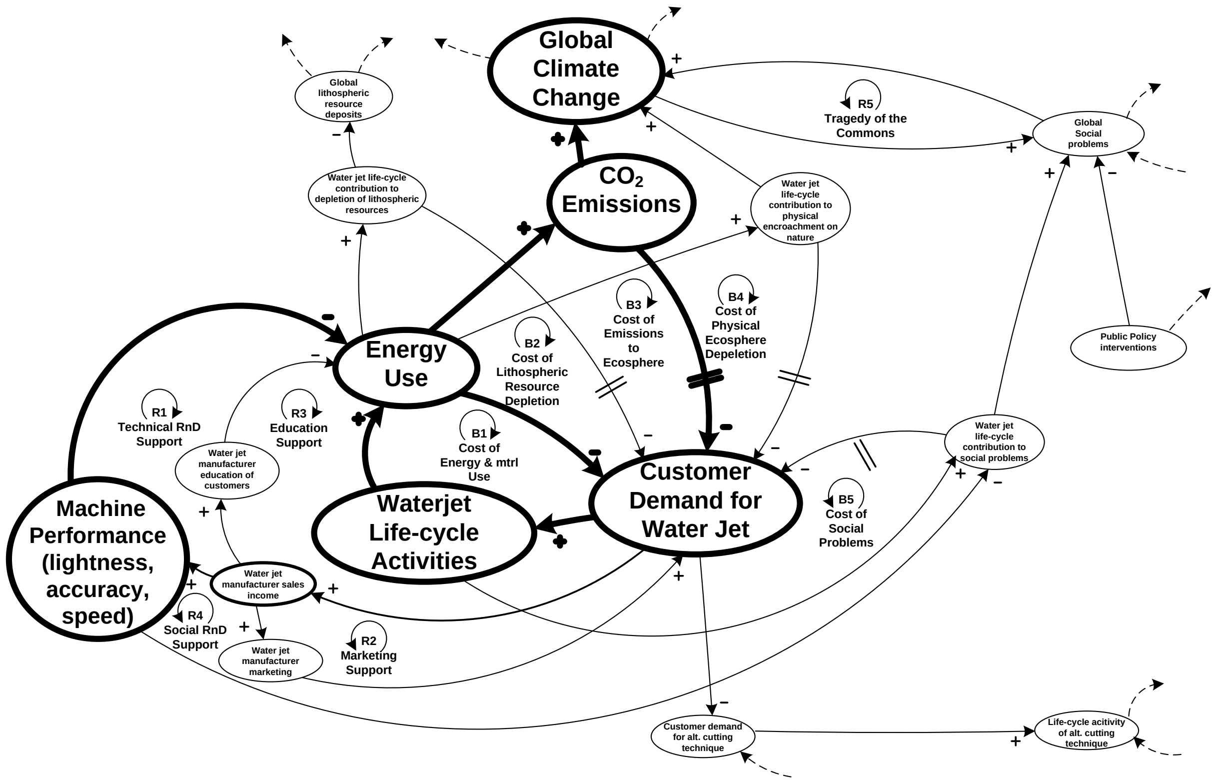

Figure 2. Causal Loop Diagram with emphasis on how improved machine performance (e.g. reduced moving weight) could reduce energy use and thereby indirectly both (i) increasing customer demand for water jet cutting and (ii) decreasing CO_2 emissions and its related contribution to climate change.

2.5 Technical Assessments of the Water Jet Case

2.5.1 Estimations and Hand Calculations

The first step in an assessment of the technical aspects of a conceptual design might be to derive a highly simplified mathematical model for which an analytical solution could be found through hand calculations. This study includes, in the present case, an estimation of stresses in the structure due to bending loads arising from normal operation of the machine. Preliminary results indicate that a lighter and less stiff design could in principle be used without risking structural failure.

2.5.2 Finite Element Calculations

A more detailed model takes the hand calculations further to include more product components, more realistic representation of included components and their interactions and boundary conditions. In the general case it then often becomes difficult to describe a product simply enough to find an analytical solution. Therefore, numerical methods, for example, the finite element method, are frequently used. Parameter studies might also be conducted to increase the knowledge about the studied system. In the present case a finite element model of the machine was used in a parameter study to sort out, for the specific design criteria, influential design parameters.

2.5.3 Virtual Machine Modeling and Simulation

Machine tools are mechatronic systems, i.e. multi-disciplinary products including mechanical as well as electronic components and intelligent computerized control systems. Design of such systems demands an overall understanding of the behaviour of the complete system. More advanced simulation tools are therefore needed, incorporating all relevant aspects of the multi-disciplinary design problem. A previously developed virtual machine concept could be used in this context [14]. This virtual machine includes a real control system, a hardware-in-the-loop simulator of the machine and a virtual reality model for visualisation. It is used within a parallel multidisciplinary design approach, simultaneously analysing the mechanics and the control, and thereby utilising interaction effects. This approach has been shown to be superior to the traditional sequential design approach [15].

The virtual machine used in this study contained several sub-models; a finite element model simulating the flexibility of the moving mechanical parts, a motor model, and a multi-body model of the transmission. The simulation model was parameterized and automated. This means that the optimization algorithm was able to influence the model by varying certain aspects of it, like its geometric quantities and/or material properties. Given the input from the sustainability assessment, all major moving machine components were identified and parameterized in the virtual machine.

2.5.4 Virtual Machine Optimization Study

A design optimization study needs to clarify both what the objective is and how design parameters can be varied to achieve this objective. Then there needs to be some algorithm that identifies which design parameter combination that best fits the objective. The primary objective of this optimization study, to reduce the weight of the main moving components, came from the TSPD sustainability assessment. Two other essential machine performance objectives, high cutting accuracy and speed (i.e. the time it takes to cut the work piece), also need to be considered. Also these objectives have sustainability implications, which were clarified from the CLD and the related above discussion. Both for this reason and for ensuring traditional competitiveness of the new alternative machine designs that were scrutinized by this optimization study, cutting accuracy and speed where not allowed to decrease in relation to current levels. Some key design parameters of the mechanics and the control were then chosen as variables in the optimization study. The design problem therefore consisted of a mixture of continuous and discrete variables. A genetic algorithm was chosen since such have the ability to solve problems of this type. By including both mechanical and control system parameters simultaneously in the optimization study, the potential trade-off between lightness and accuracy and/or speed could actually be avoided in this case. The optimization study revealed a significant potential for design improvements. The weight of the main moving components can be reduced by more than 30 percent, at the same time as the cutting accuracy can be improved by more than 60 percent at maintained cutting speed (small increase by 2 percent).

2.6 Societal Sustainability Consequences

The above described CLD (Figure 2) could also be used to estimate societal consequences of design changes suggested by the technical assessment. In this case, the effect of reduced moving weight was in focus and in particular how this would lead to lower energy use and, indirectly, lower CO_2 emissions and, in turn, less contribution to global climate change. In general, energy savings often make both the organization's and society's transformation towards sustainable energy systems easier for several reasons. Energy savings could, for example, reduce costs and thereby enable investments in substitution to new renewable energy sources. Since not the whole previous amount needs to be replaced by new energy sources (due to energy savings), the transformation could proceed faster towards renewable and more sustainable energy sources.

If electricity use is proportional to the moving weight then it would be possible to reduce electricity use by up to 30 percent. The power use for electric motors driving the moving parts of an average water jet cutting machine in normal operation is about 3 kW and it normally runs 1500 hours per year. Furthermore, if it is assumed that the improved water jet cutting machine replaces cutting equipment that is at least as polluting, the 1 kW of power savings could be assumed to be a minimum net reduction. Saving 1 kW for a machine that runs for one operating year (1500h) would translate into 1500 kWh per year. Assume that the machines are used in the United States. The above energy savings would then (based on the mix of energy sources in US electricity [23] and the CO_2 emissions per kWh of those energy sources [24]) translate into a CO_2 emissions reduction of 315 kg per machine and year. This quantification of energy savings (dematerialization) could then be used in various scenarios.

3. RESULT

The water jet case shows the potentials for an integrated sustainability and technical assessment. The working procedure is interactive and iterative in order to finally suggest what design variables that have the most significant socio-ecological impacts (Figure 3).

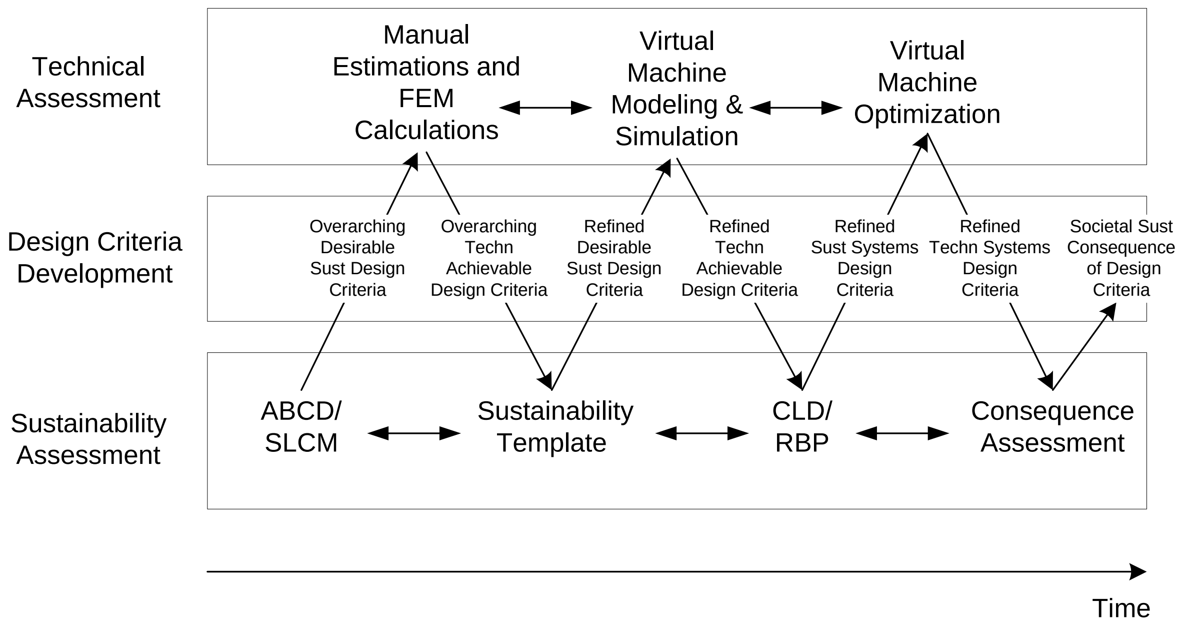

Figure 3. Gradual refinement of product design criteria through an integrated and iterative assessment.

The new integrated assessment procedure could be expressed in general terms (Figure 4). Overarching sustainability assessment methods/tools, should first scrutinize water jet cutting (and to some extent competing techniques such as laser- plasma- and gas cutting) to identify prominent sustainability problems from present-day flows and practices ("societal indicators"). Ideas of long-term principle solutions and visions are also generated, and then based on this a first rough idea about likely desirable changes in machine properties is obtained. Introductory technical investigations are then performed to assess if/how these particularly desirable changes in machine properties could in principle be realized through changes in design variables. Obtainable changes are then fed back to a new and more refined sustainability assessment to find out the societal implications of these changes. This may in turn result in other desirable design changes, which may call for a new and more refined technical assessment, and so on.

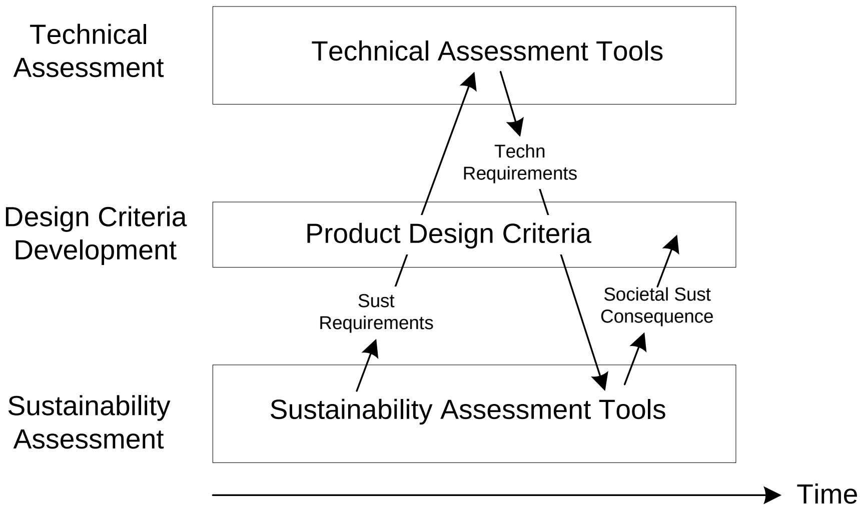

Figure 4. A suggested generic working procedure for an integrated and iterative sustainability and technical assessment.

4. DISCUSSION & CONCLUSIONS

This paper suggests a working procedure for a combined sustainability and technical assessment in order to facilitate design optimization informed by a societal perspective. Preliminary ideas are presented through a case study of water jet cutting. Both overarching and more detailed sustainability-related and technical methods/tools are used iteratively to arrive at design changes that are likely to support sustainable development of society.

The initial sustainability assessment resulted in a list of desired changes, in particularly sustainability related product properties for water jet cutting machines. This included the weight of the moving parts, the life-span of the product components, the recycling system of the abrasive material and a cleaning system for the process water. Out of these, a reduced weight of the moving parts was introduced as an added goal in the technical optimization study. The main reasons for focusing on this single property were that (i) moving weight is connected to energy consumption during use and this is currently a major contributor to sustainability problems like climate change, (ii) the moving weight is relatively easy to change through material choices and geometry optimization, (iii) the moving parts could also be modeled separately from other complicated subsystems like the water jet and its penetration of the material that is cut, and (iv) the main purpose of this paper is to introduce some preliminary ideas for - and not to perform a full - combined sustainability and technical assessment.

The technical study resulted in a *theoretical potential* for reducing the weight of the main moving parts by more than 30 percent, while simultaneously improving cutting accuracy by more than 60 percent and increasing the manufacturing speed by two percent. Reduced weight also indirectly reduces the need for steel and other materials that the water jet machine consists of. This means that negative sustainability effects from those material life-cycles could be reduced as well. Other authors have suggested a computer model for optimizing *the practical use* of a water jet cutting machine [16]. That study suggests that it could be possible to increase the cutting speed and thereby reduce the operating and maintenance costs by changing operational parameters like abrasive flow rate, water pressure and number of used cutting heads. As found in the current study, an increased cutting speed could be beneficial also from a sustainability point of view.

Product development considers several criteria like costs, quality, ease of maintenance, etc. It is here suggested that a necessary addition to this picture is the consideration of socio-ecological implications of product properties. An integrated and iterative procedure should also be used to reach a satisfactory solution from technical, business-economic and socio-ecological perspectives. Furthermore, it is suggested that such sustainability-informed optimization should be included particularly in the early phases of the product development process. This would aid the ability to make well-informed decisions early on and thus potentially identifying innovative solutions for the evolving sustainability-driven market. It would also potentially avoid costly and difficult changes later in the product development project. The experience from the case study indicates that the suggested working procedure should be able to add information about socio-ecological impacts of product properties and influence design criteria used in prioritisation situations during product development.

Future research will address how to further clarify how technical and sustainability-related assessments could be effectively coordinated to support prioritization in product development. Another upcoming research focus is the prioritisation process itself. Future studies will also include other products and methods/tools like quantified sustainability-related systems modeling and simulation and life cycle assessments.

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