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MATERIAL CRITICALITY METHOD - PRODUCT VULNERABILITY FROM A SUSTAINABLE BUSINESS PERSPECTIVE

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1. Introduction

In the state of the art paper on industrial sustainability, focused on definitions, tools, and metrics, presented by Arena et al. [2009], the authors stated that in order to reach more sustainable solutions, the product development team must know what sustainability means, how sustainability can be achieved, and how sustainability can be measured. A novel appproach for defining a sustainability design space was suggested in [Hallstedt 2015a]. Also early testing of its application for generating new concept solutions, assess processes and develop road-maps for product improvements have taken place at a case company, and some first results are presented in [Hallstedt 2015b]. The purpose with the approach for defining the sustainability design space was to identify the most important sustainability aspects and to be able to include these early in the product innovation process.

One common sustainability-related aspect decided early in the product innovation process, for many manufacturing companies, is the choice of material. From a business perspective there is a risk if a company becomes dependent on a material that may cause harm to business objectives. This can happen if stakeholders, e.g., customers, governments, and users respond to sustainability impacts due to this material, which may result in tougher legislation, higher market price on the material, less customers or users of the final product. For the company this is a risk that then may result in higher cost and less income for the company. In [Lloyd et al. 2012a], this situation is defined as “environmental business risk”.

Generally there is an increased interest in material criticality. A proof of concern for material criticality is the increased numbers of published papers on materials availability [Speirs et al. 2013]. One reason for the interest is that the developed nations have been increasingly dependent upon imported materials from less stable supplying regions. Another reason is that some nations’ policies have a potential to disrupt the operations of global markets. Also, a clear recognition of the social and environmental consequences from extracting some raw elements constitutes a reason to care. An additional reason to have knowledge about which elements are considered critical is an increased concern of concentrated production sites for some elements creating supply monopolies [KPMG 2014].

1.1 Purpose

The purpose of this study is to validate a sustainability compliance index as part of a defined sustainability design space at a case company. The purpose is also to suggest an approach for how to identify potentially critical materials, with focus on alloys, and to suggest a method for how to estimate the vulnerability of a product due to the material criticality. In addition, some first results from industrial evaluation are presented. The resulting support, a novel method and a material criticality list, has the aim to strategically guide early product design decisions as regards material criticality.

1.2 The case company and research approach

The case company for this work is an engine component manufacturer in the aerospace industry and was selected as their research and development department wanted to increase the capability to integrate a sustainability perspective in their decision-making system. Further on it was expected that the engineers and designers in future will be faced with the problem to explore sustainability-related issues to identify business opportunities for technologies in new applications. The company therefore identified the need for suitable support tools in their decision-making system.

Based on a defined sustainabilty design space for the case company [Hallstedt 2015a] it was clear that one of the most important sustainability aspects to consider during the early phases of the product innovation process was the degree of risk materials, so called critical materials. A material criticality list for the alloys was therefore developed for the case company, included in the suggested method with the intent to be used as decision support in early product development.

This research is based on exploratory, descriptive and prescriptive studies [Hallstedt et al. 2013a], [Hallstedt 2015a, 2015b], according to the design research methodology (DRM) proposed by Blessing and Chakrabarti [2009]. The results from those earlier research studies gave guidance for a sustainability compliance index development that was used to build the suggested prescriptive method to identify the potentially crucial materials from a sustainable business perspective. This research uses an action research- based approach (AR) [Avison et al. 1999]. 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 Coghlan 2009]. The theoretical approach is based on “set-based engineering” principles as described by Sobek et al. [1999] and basic principles for global socio-ecological sustainability [Broman and Robèrt 2015] as well as previous research in the area of material criticality assessments, e.g., [Erdmann and Graedel 2011], [Speirs et al. 2013].

2. Sustainability design space

To be able to guide decisions and search for possible solutions in the early product innovation process a design space needs to be defined. A sustainability design space as described by Hallstedt [2015a] consists of three parts: *i) Strategic Sustainability Criterion* is the ideal long-term sustainability target and something to strive for; ii) *Tactical Sustainability Design Guideline* defines the prioritized sustainability aspect that supports development towards the related long-term strategic sustainability criterion; iii) *Sustainability Compliance Index (SCI)*: constitute the levels of compliance for each of the strategic sustainability criteria. The strength with this approach is that the strategic sustainability criteria support the definition of what sustainability means for the company. In addition, the tactical design guidelines support the description of how sustainability can be achieved, and the SCI supports the way of how sustainability can be measured. In this way the developed strategic sustainability criteria, tactical design guidelines and SCI altogether support the company in becoming more sustainable, according to the findings by Arena et al. [2009].

The long-term strategic criteria, the tactical sustainability design guidelines and the SCI result from a process described in detailed by Hallstedt [2015a]. In short, the criteria development is conducted in three steps: i) collect existing sustainability-related requirements and tactical design guidelines for the particular company or industry branch; ii) review all product life-cycle stages through sustainability principles (see below); iii) select the tactical guidelines using meta-criteria adapted from [Schmidt and Butt 2006], [Dreyer 2010]. The steps i) and ii) can be conducted in parallel and independently of each other. The criteria that are derived from these two steps represent short-term and long-term sustainability criteria and will be synchronized later, before step iii). See Figure 1 where the process is schematically described.

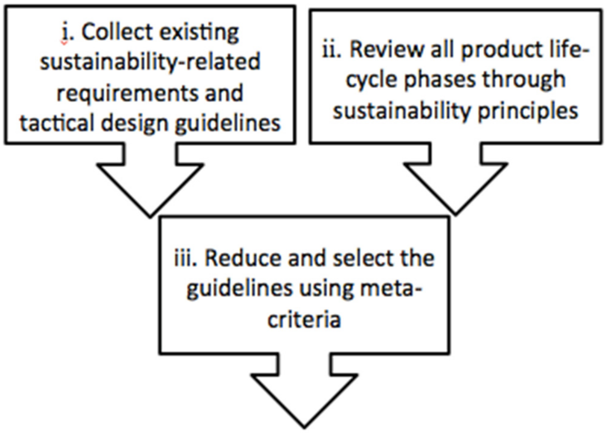

Figure 1. The process steps to develop the sustainability criteria

The Sustainability Principles (SP) at the basis of a 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 people are not subject to structural obstacles to... [4] health, [5] influence, [6] competence, [7] impartiality, and, [8] meaning-making.□ [Broman and Robert 2015], [Missimer 2015]. 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], [Vergragt and Quist 2011].

For a deeper qualitative assessment to answer to what degree a product concept performs in relation to a sustainable solution, a SCI has been developed [Hallstedt 2015a]. Each criterion in the overarching sustainability matrix is divided into four SCI levels. See Figure 2 for how the SCI levels are defined. The development of the different levels was inspired by and adapted from other maturity or readiness scales such as the Technology Readiness Level [Mankinds 1995], Sustainability Integration Stages [Willard 2005] and Capability and Evolution Levels [Pigosso et al. 2013]. The purpose of the SCI is to support both active search of- and a ranking of concepts and a comparison of different alternatives from a sustainability perspective.

Sustainability Compliance Index (SCI) scale	
SCI 9	The strategic sustainability criterion is fulfilled. Reached excellent level.
SCI 6	Have implemented a strategy with concrete actions for how to move step-wise towards more sustainable solutions. Moving strategically towards the excellent level (SCI9).
SCI 3	Compliance with socio-ecological related regulations. A low but acceptable level.
SCI 1	Lowest level of sustainanability compliance. Not acceptable level.
0	No information to score a SCI value. Need more research and investigation.

Figure 2. Sustainability Compliance Index scale

3. Why material criticality list is relevant

A material risk list is relevant from both a business perspective and a sustainability perspective. A material risk list should give guidance in the scoping/emerging phase, when doing concept development and selection. If, for example, a more sustainable alloy is chosen from start the business risk will be reduced. The knowledge of any possible vulnerability of product concepts due to material criticality could support the product development team to find more proactive solutions and identify alloys that need to be taken care of in closed loops. If a certain alloy is considered as critical but cannot be exchanged, it is important to find solutions for increased resource efficiency according to the circular economy principles [Ellen MarcArthur Foundation 2013]. A case study on this topic was presented in [Hallstedt et al. 2013b] and a modeling and simulation approach to assess sustainability and value consequences for different resource efficient scenarios was suggested.

A value of knowing about the material's potential criticality can also support innovation development including how to realize material closed-loop solutions. Since materials used are transparent to the supply chain, there is a potential to develop business relations and collaboration in the value-chain. Potentially, the list of material criticality can be shared and expanded within the value-chain (suppliers and down-stream actors) and thus allowing for resource effient and re-use business scenarios. Such development of business relations can be developed to achieve more sustainable and more resource efficient solutions.

4. Material criticality assessment

Previous research suggest that there are several dimensions to estimate the material criticality for a product. Future availability of the material in relation to supply risk, vulnerability to supply risk, and sustainability risk in relation to socio-ecological consequences will have impact on the material criticality [Graedel et al. 2012], [Lloyd et al. 2012b], [Speirs et al. 2013]. In this study the estimation of the vulnerability of products in relation to business risk, due to its dependency of critical materials, is of interest. Therefore each of the materials, relevant for the case company's products, was assessed against future availability risk and sustainability risk.

There are several studies, e.g., [Erdmann and Graedel 2011], [Speirs et al. 2013], with recommendations of aspects of what to include in an assessment of elements in relation to availability risks, see Figure 3. These aspects cover geological measures, co-production, monopoly supply, political stability in sourcing countries, recyclability, environmental regulation, and substitutability. The methods 1-6, listed and described in Appendix A, are used for this study and cover the aspects mentioned. These methods are developed to identify material criticality on element level. All six are used in the assessment as these have all different focuses, time scales and objectives. They also use different scales and methods to judge the criticality. In addition, very few methods have assessed the same elements. Therefore, in order to get a good overview of the criticality from an availability risk perspective for the case company's elements these six studies and methods were used.

In addition to these six methods, three sustainability risk methods, listed as 7-9 in Appendix A, are used to indicate the sustainability risk. These are selected as they indicate if the extraction and usage of the element are causing or will cause negative sustainability consequences in future. These three aspects, which are conflict minerals, phosphorous content and contamination factor, capture important sustainability aspects but do not give a complete picture of the sustainability consequences during a product life (for that more detailed analysis is needed). However, these aspects give a signal of the seriousness level and will therefore give an early warning of the element's criticality level and possible need for more detailed analysis. Existing data regarding these three aspects is also available in databases or published lists.

One of the social sustainability indicators used in this study is "conflict minerals". Conflict minerals are elements that are mined in conditions of armed conflict and human rights abuse. These minerals are sold to get money for continuing a civil war and at the same time force people to extract the minerals, which cause a social disaster [Dodd-Frank Wall Street Reform and Consumer Protection Act, § 1502 2010]. Another social indicator is the content of phosphorous, which is an element essential for agriculture. This is important, as the current global reserves of easily accessible phosphorous will be depleted within the next 50 to 100 years at current consumption rates and could lead to less production in agriculture [Cordell 2010]. The future contamination factor is the third sustainability aspect used for this assessment. The contamination factor indicates if there is a risk of systematic increase in the concentration of a particular element in nature depending on the ratio between anthropogenic flows and natural flows [Klee and Graedel 2004].

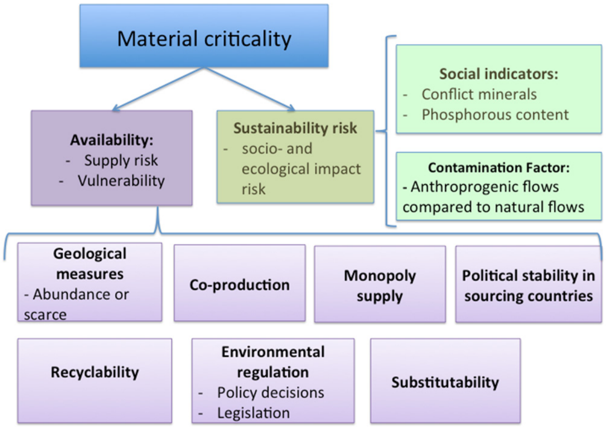

Figure 3. Aspects in the different evaluation methods

5. Material criticality assessment and the results for case company's alloys

The material criticality list was developed based on the methods described in the section above and in Appendix A. The material criticality list shows which elements are critical in each alloy. To assess which alloys are critical the SCI, described above, is used to give a first, quick and qualitative result. The SCI indicates to what degree the alloy can be regarded as compliant with the long-term sustainability criteria. The specific SCI levels, related to the critical materials, are shown in Figure 4.

Decision aspects concerning product life cycle phases	**SCI**	**Sustainability aspects guided by Sustainability Principles 1: Nature is not subject to systematically increasing concentrations of substances from the Earth's crust.**
Raw material: materials and chemicals that are used for product components and /or its production.	9	No risk materials used according to material criticality list.
	6	No alloys that includes conflict minerals, or, high supply risk elements are included, but still includes elements with high anthropogenic flows compared to natural flows.
	3	No alloys that includes conflict elements are used but high supply risk elements are included.
	1	Alloys that include conflict minerals and likely other risk elements.
	0	Do not know if and what risk materials that are present in alloys today.

Figure 4. Sustainability Compliance Index used for a qualitative criticality evaluation of alloys

The qualitative assessment of the alloys using the SCI levels gave a first indication of which alloys are most critical. The result from the SCI also gives information and answers to why the alloys are considered most critical. It describes, for example, which elements that could be conflict minerals in the alloys.

To distinguish between the most critical alloys and find which is *the worst critical* alloy a more detailed ranking is needed. This ranking of the alloys depend on i) the number of methods that have assessed the element as critical, ii) the number of elements that are judged as critical by several methods, and iii) the amount of these elements in the alloy. The result at the case company was a list based on the ranking of the current alloys that indicated which are the most important materials from a sustainability perspective to focus on and find alternative solutions.

6. In order to estimate the vulnerability of a product due to material criticality

When it is known which alloys are worst from a material criticality perspective it is of interest to calculate the vulnerability of a product that is dependant on this critical alloy. Vulnerability means here the significant increase of cost in relation to other cost and the probability for this to happen. In other words, a significant and probable cost increase constitutes a clear business risk. The vulnerability should be calculated for the product concept and based on the estimated increase of material cost due to material criticality in relation to the likelihood of increased cost.

6.1 A method to estimate the vulnerability of a product

The result of this work is a suggested method including an approach for how to identify potentially critical materials, with focus on alloys, and a process including four steps for how to estimate the vulnerability of a product due to the material criticality. The resulting method is developed in an action research-based approach for an aerospace company. However, the result is also considered generic for other industries which are dependant on advanced alloy materials. Therefore this method for how to identify potentially critical materials from a sustainable business perspective can be organized into four steps;

Step I: Identify potential critical elements

Assess each element in the alloys using a variety of well known material assessment methods based on existing data to cover both the availability risk and the sustainability risk. [See Appendix A]

Step II: Grade the level of criticality for each alloy

Each alloy is assessed using the SCI which give a qualitative result and detailed information of the SCI level for each alloy. The most critical alloys from a sustainability perspective are identified.

Step III: Comparative sustainability ranking of alternative alloys

The most critical alloys from step II are assessed and ranked in relation to: a) the number of elements considered critical; b) the number of elements considered critical from at least two assessment methods; and c) the amount of these elements (for those elements ranked critical in at least 2 assessment methods).

Step IV: Vulnerability assessment of product and production concepts

Using the results from the previous steps the vulnerability of each concept can be assessed, form a business risk perspective . This means that based on the information from the steps above it is possible to make estimations on changes of material costs in relation to likelihood as well as the increase of material cost in relation to other costs. A previous example for how to calculate the vulnerability is presented in [Lloyd et al. 2012a].

7. Evaluation of the suggested method at the case company

7.1 Stakeholder group

A stakeholder group of ten persons with many years of experiences (most with more than 8 years) at the case company was introduced to the method. The stakeholder group had many different roles, e.g., material engineers, chief engineers, design engineers and envionmental engineer, and were asked questions on their view of the SCI and method usefulness, of possible users, and the possibility regarding integration of the method in the risk assessment process at the company.

7.2 Method and SCI usefulness and possible users

The stakeholder group was of the opinion that the SCI index can be useful to increase the communication around sustainability and support in business development and that it can connect design to business development if the estimated potential cost is also included. The stakeholder group also considered that the SCI could be important to use in the development and production of new products. However, the result from this assessment needs to be compared and weighted in relation to other requirements.

In general the stakeholder group was positive to the method and believed that it can give decision support in material development and selection in early product innovation phases. However, for some products there are few possibilities to choose between different materials as the degree of freedom is limited and therefore a support in selecting a material is not always relevant. On the other hand, the stakeholder group considered that the method, to some extent, still could be beneficial for the selection of more sustainable alloys; to identify which alloys to phase out; to identify alloys for closed-loop solutions; and to enhance collaboration in the valuechain. Some of the stakeholders believed that this method also could be used to: drive the general awareness about sustainability at the company; show that the company is proactive, and suggest other alternatives that could create value in a business case.

Some of the stakeholders also identified potential risks and weaknesses with using the method such as: it has to be linked together with other databases to be sure data is not missed; and, if decisions are based on this method it may be too proactive in relation to competitors and this could mean higher product costs. Also, it was considered that the suggested approach may be a good base to build on, but to be implemented senior management need to commit and accept using this sort of assessment for decision making. In general, all agreed that it has some potential to be useful and implemented. Therefore it needs further testing and validation. In addition to this some data model support may be needed to do regular updates, especially if many alloys are added to the material criticality list. Possible users for this type of method could be the design team together with the purchasing team. It could also be a method-owner for design practise regarding Sustainable Product Development in future.

7.3 Alternative methods

Similar assessments are not done on a regular basis at the company. A previous Environmental Impact Assessment (EIA) had several years ago included an assessment of alloys using data from the EPS-method that aims to support environmental priority strategies in product development [Steen 1999]. The result was, however, not done related to material criticality for supply risk and sustainability but rather the environmental load for extracting the different elements. The reasons for not doing these kinds of assessments today are not clear. It could depend on lack of time and resources but also because the awareness in the area is not enough.

7.4 Integration in risk assessment

Today there is no calculation of vulnerability due to critical alloys used in the products at the case company. However, the stakeholders considered it possible to include this as part of the risk assessment. In addition, all stakeholders believed that it could be beneficial to do so, both in terms of increased awareness and to ensure viable supply chains.

8. Discussions and future work

This paper presents a novel method, including a material criticality list and SCI, that aims to strategically guide early product design decisions as regards material criticality. In order to make sustainability issues tangible in engineering design teams it is important to provide a clear concept of sustainability and then link this to relevant matters to the design work. Inspiration for further research on this topic can build on the approach for mapping relationships between environmental parameters and technical requirements presented in [Romli et al. 2015]. In this paper, a concept of sustainability is enabled through expressing a Sustainability Design Space including SCI and links this to material selection of product concepts. A jet engine component design team evaluated the material criticality method. It was understood that the method increased communication and clarification about materials criticality. Further, it became apparent that the material criticality method provided a collaboration link between the design team and the business development team. This is necessary since engineering design teams need to justify alternative design arrangements in relation to their business impact.

From a sustainability perspective a material alloy could contribute to a violation of the Sustainability Principles [SPs] [Broman and Robèrt 2015]. The extraction, production, distribution, usage, and end-of life phase of the alloys may have concerns regarding all these SPs. A full picture of sustainability is not covered in this first approach for estimating the vulnerability of a product due to the material criticality. As described earlier, the aspects of conflict minerals, phosphorous content and contamination factor are selected as they indicate if the extraction and usage of the element are causing or will cause negative sustainability consequences in future. These capture important sustainability aspects but do not give a complete picture of the sustainability consequences during a product life, for that more detailed analysis is needed. However, these aspects give a signal of the seriousness level and will therefore give an early warning of the element's criticality level and possible need for more detailed analysis. Existing data regarding these three social sustainability aspects is also available in databases or published lists. However, it is also important to note that to do an assessment of material criticality there are many uncertainties that should be taken into consideration if used in a decision situation. The uncertainty lies partly in the fact that there are some subjective judgements of some supply risk aspects, and partly that there is uncertainty in the data sources. In an assessment the uncertainty needs to be acknowledged and have high transparency.

In the very early phase of the product development process the data and information is not available regarding issues related to emissions, means for physical degradation of nature and details of social sustainability consequences. Therefore it is important to also assess the product concept further on against the other sustainability criteria, which for the case company was identified to 22, before a final decision of product concept is taken. However, it makes sense to make investigations as early on as possible and make use of some available data that can give an early warning of potential business risks. If a proposed solution indicates a potential problem that can affect the business risk it should be avoided and then detailed assessment is not needed as alterntive solutions instead should be developed. Further on in the product innovation process there are fewer numbers of alloys/materials to consider or maybe even just one alternative. The next step in order to reduce the sustainability impact from materials perspective would be to also have a dialogue with the suppliers. Guidelines for more sustainable supply chain management have been proposed by Bratt [2014].

One identified strength is that this method provides transparency for the user. This is a dynamic area and the data used for the element assessment will be updated as more research and knowledge in this field will grow [Speirs et al. 2013]. The users at the company could therefore go to the sources and update the material criticality assessments regularly. Another strength is that the SCI gives the information to the users of which elements that cause the specific SCI level. This could therefore open up for a discussion of resource efficiency, closed-loop solutions, as well as research inititatives for alloy- or element substitutability. In a product development project dealing with products having long-life times, for example components used for aeroplanes, there is a need to do a vulnerability assessment as part of a risk assessment to estimate the probability for a change.

Other material criticality assessment such as the EPS system [Steen 1999], which includes a simplified assessment of materials, has less transparency in terms of explaining why the result for different elements have different environmental impacts. In addition, the social sustainability perspective is lacking and it is not clear to the user which data scources are used in the element assessment. However, the strength of these types of methods is that these instead give a user-friendly approach, which is time efficient for the user.

Step IV of the proposed method, is a calculation of the vulnerability from a sustainable business perspective of a product concept that will be further explored in continuous research at the case company and presented in future publications. The result from the evaluation of the method at the case company indicated that the method has potentials to be implemented and used after further testing, validation and some improvements. In a future validation case three alternative candidate alloys will be compared for a component included in a new engine family. The method to estimate the vulnerability for each concept due to the material criticality will be conducted. In this way a more in-depth investigation will explore, test and identify improvement potentials of the method to increase the implementation capability.

To develop a global or even national list of relevant critical materials that can be used by everyone is not possible [Lloyd et al. 2012b]. One assumption, though, is that the presented material criticality list of the alloys for the case company also is relevant for the whole aerospace industry. The main contribution of this work is however the proposed generic method, relevant for all industries using advanced material alloys, to identify potentially critical materials from a sustainable business perspective.

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Appendix A

Methods with focus on availability	Assessments methods	Reference	Objective
	National Research Centre [US]	US Research Council [2008]	Identify critical materials and methodology develop. for the US
	JRC Critical Metals [EU]	Moss et al. [2011]	Identify overall supply risk for metals in low-carbon technologies
	European Commission [EU]	European Commission [2014]	Identify critical raw material for the EU
	Yale methodology	Graedel et al. [2012] Nassar et al. [2012] Nuss et al. [2014]	Identify the criticality through detailed methodology to generate utilitarian assessments. Displays the criticality from 3 perspectives: corporate, national, and global.
	Oakdene Hollins study [UK]	Morley and Eatherley from Oakdene Hollins [2008]	Identify insecure materials to the national economy / defence of UK caused by restricted access to specific materials.
Method focus on supply risk	BGS Relative Supply Risk Index	British Geological Survey Risk list [2012]	Give indicator of relative risk in 2012 to the supply of 41 elements.
Methods with focus on sustainability	Anthropogenic flows	Klee and Graedel [2004]	Give the ration between human mobilization versus natural mobilization.
	Conflict mineral	Dodd-Frank Wall St. Reform & Consumer Prot. Act, §1502 [2010]	Provide a list of elements that are very likely are conflict minerals.
	Phosphorus study	Cordell [2010]	Specific indicator on phosphorus.

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