SUSTAINABILITY INTEGRATION IN A TECHNOLOGY READINESS ASSESSMENT FRAMEWORK

Hallstedt, Sophie (1); Pigosso, Daniela (2)
1: Blekinge Institute of Technology, Sweden; 2: Technical University of Denmark, Denmark

Abstract

In this paper, an approach to systematically include sustainability into the Technology Readiness Levels (TRL) is proposed. The aim is to answer the question "how can sustainability provide systematic guidance in technology development and early product development?". Results from a case study illustrate that the suggested approach can support i) the inclusion of sustainability into the early design stages, when only limited data and information is available; ii) the enhancement of the comprehensiveness of sustainability and ease of use in the day-to-day engineering working environment; and iii) simplified sustainability assessments without being too simplistic and/or reducing the sustainability scope. The proposed approach is being co-developed in collaboration with a case company, and tests on an actual technology development project are planned. The next steps are related to the application of the proposed approach in other companies to test its robustness and enhance its generalization for application in diverse contexts.

Keywords: Technology readiness level, Ecodesign, Sustainability, New product development, Early design phases

Contact:
Dr. Sophie Hallstedt
Blekinge Institute of Technology
Department of Strategic Sustainable Development
Sweden
sophie.hallstedt@bth.se

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1 INTRODUCTION

1.1 Needs and challenges to assess sustainability in early phases of technology-and product development

Global society currently encounters unprecedented challenges: climate change, resource depletion, chemical contamination and increased social problems (Rockström et al., 2009). Those global effects come with a set of challenges from a business perspective, such as increased material and energy volatility, harsher legislation, etc, which can be turned into opportunities when properly tackled. It is therefore important that companies integrate sustainability considerations into their business processes, especially in the early stages of product and technology development, which largely defines the sustainability performance of the developed artifacts. Integrating the breadth of sustainability into product development is labelled sustainable product development (SPD) or sustainable design (Gagnon et al., 2012). Sustainable product development relates to the integration of sustainability into the early phases of the product innovation process, including a life cycle thinking.

Nevertheless, the integration of sustainability into the early phases of technology and product development can be challenging (McAloone and Tan, 2005). Firstly, one main challenge is related to *the breadth and complexity of sustainability* (Broman et al., 2017), which leads to a risk of suboptimisation and long-term sustainability consequences (Byggeth et al., 2007). The second challenge is the *limitation of time and of data availability in the early design stages* to analyze sustainability in a rigorous manner (Ullman, 1992), without compromising the completeness of sustainability or the product life cycle (Schöggl et al., 2017). The third challenge is that there is a difficulty of assessing and communicating sustainability to designers and engineers. This may be mainly due to *the problem of showing numbers and 'hard facts' related to the value generated by sustainability-oriented decisions* (Hallstedt et al., 2015).

These challenges indicate that there is a need for methods and tools that are able, already in the early design stage, to balance sustainability requirements with other interests, highlighting how a sustainable design choice can create value for customers and stakeholders, hence generating market success in the long term. A more sustainable design choice can result in resource efficient solutions throughout the product life cycle. Applied research in operational tools and methods that support SPD aims to strengthen businesses to overcome the challenge to shift towards more sustainable solutions, in addition to increasing the companies' competitiveness.

There are several developed generic support tools summarized in e.g., Salari and Bhuiyan (2016) and Buchert et al. (2014), which aim to support design teams in integrating sustainability in the early design stages and provide guidance in their design decisions. However, these methods lack a combination and integration within the design process; inclusion of a whole life-cycle perspective during product development; and, inclusion of all dimensions of sustainability. In addition to this, few support tools include a long-time perspective, which makes it harder to take actions for issues that might come up later (Hallstedt et al., 2013).

In order to be able to reduce potential risks and prevent sustainability consequences that cause cost over-runs, there is a need to measure the current sustainability level, set sustainability targets, measure the progress and visualise this on both a process- and product level (Arena et al., 2009). In this paper we propose an approach that aims to support sustainability implementation into the technology development process, by using the Technology Readiness Levels (Mankins, 1995) as a framework for integration.

1.2 Technology Readiness Levels

Technology Readiness Levels (TRL) were introduced in the mid-1970s by the National Aeronautics and Space Administration (NASA) as an approach to allow a more effective assessment and communication of the maturity of new technologies (Mankins, 1995). Since its development, TRLs have been adopted by a varied set of companies and organizations, especially from the aeronautics sector (Nakamura et al. 2013), in a varied number of applications. Some of the applications are related to dualinnovation and co-development of new technologies and products (Brilhuis-Meijer et al., 2016), evaluation of TRLs during product development (Hicks et al., 2009), assessment of composites recycling technologies (Rybicka et al., 2016), Life Cycle Assessment of emerging technologies (Gavankar et al., 2015) and manufacturing readiness of complex systems (Atwater and Uzdzinski, 2014). Considering the high

uncertainty and exploration/experimentation as intrinsic characteristics of the technology development process (Högman and Johannesson, 2010), the TRLs are commonly defined by a combination of nine levels (Table 1), which are characterized by a set of specific activities and deliverables. The assessment of the TRL of a given technology is performed in an assessment, so-called technology readiness assessment (TRA). TRAs are usually carried out several times during a formal technology development process, from system analyses and conceptual design studies, to decision-making regarding design options and full-scale development. TRAs include a clear understanding of the performance objectives, including engineering and operational measures of performance. One of the challenges mentioned for the application of TRL and TRAs is related to the establishment of the right metrics to measure the technology/system development, primarily from a performance and cost perspective (Mankins, 2009).
With the enhanced adoption of sustainability in a technology development context, the identification of sustainability-related metrics becomes increasingly relevant.

Table 1. Technology Readiness Levels (adapted from (Mankins 2009))

	Technology Readiness Levels
TRL 9	*Actual system “proven” through successful system and/or mission operations*
TRL 8	*Actual system completed and qualified through test and demonstration*
TRL 7	*System prototype demonstration in the planned operation environment*
TRL 6	*System/subsystem model or prototype demonstration in a relevant environment*
TRL 5	*Component and/or breadboard validation in relevant environment*
TRL 4	*Component and/or breadboard validation in “laboratory” environment*
TRL 3	*Analytical and experimental critical function and/or characteristic proof-of-concept*
TRL 2	*Technology concept and/or application formulated*
TRL 1	*Basic principle observed and reported*

1.3 Purpose and aim

The purpose of this research is to give answer to: *How to systematically give sustainability guidance in technology-and early product development?* An approach for how sustainability, from a qualitative approach to a quantitative approach, can be integrated into the technology development process, by using the TRL as a framework for integration is presented. The approach is expected to systematically give sustainability guidance in early technology-and product development. The main contribution of this research is to suggest how sustainability aspects can guide and assess the development of technologies in the early design stages. The goal is to balance comprehensiveness (i.e., not being unnecessarily simplified in a reductionist way) with the ease of use in the day-to-day engineering working environment.

2 RESEARCH APPROACH

2.1 Prescriptive approach to integrate sustainability into TRL

The idea of integrating sustainability into the TRL was initiated by a design team at the case company (an engine component manufacturer in the aerospace industry) during a SPD-workshop , which explored the inclusion of a sustainability perspective in their technology development process. The Technology Readiness Assessment (TRA) was identified as the key tool in which sustainability could be integrated to support its consideration during the technology development process. TRA is an implemented evaluation tool at the case company that is used to evaluate and assess all new technologies from different perspectives, such as health and safety, risk, manufacturing, design, materials etc.
Three guidelines were defined for the development of the suggested approach, based on needs to meet the challenges in implementing sustainability in the day-to-day engineering working environment:

1. Systematic approach that continuously include sustainability guidance and assessment through the different TRLs. *This meets the challenge of including sustainability even in the earliest stage when limited data and information is available;*
2. Shifting from overarching to detailed picture of sustainability, still including a full socio-ecological

sustainability perspective and the product life cycle. *This meets the challenge to balance comprehensiveness with the ease of use in the day-to-day engineering working environment*;
3. Shifting from qualitative to quantitative approach. *This meets the challenge to balance the engineers' desire for hard facts related to the value generated by sustainability assessments without being too simplistic and/or reducing the sustainability scope*.

This research uses an action research (AR) -based approach (Avison et al., 1999) and to some extent a participatory action research (PAR)- based approach (McIntyre, 2007). 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). In the present study, one of the researchers interacted tightly with the product design team at the case company. The researcher facilitated the SPD-workshop, had follow up meetings and later discussed adaptation and testing of the proposed approach at the company. The product design team included roles such as material engineers; procurer; design lead; and, a project leader.

Previous exploratory, descriptive (Hallstedt et al., 2013) and prescriptive studies (Issa et. al, 2015; Hallstedt, 2017) were used as a base for this research, which is mainly prescriptive. The two steps taken in this research are:

1. Identification of prioritized sustainability criteria for technology and product development. This step is supported by an approach to define and develop sustainability long-term criteria, related short-term tactical design guidelines, and sustainability compliance index (Hallstedt, 2017). The sustainability compliance index gives a qualitative measure of a product or process performance in relation to a sustainable solution, based on the definition of a Sustainability Design Space, which consists of three parts (Hallstedt, 2017): Strategic Sustainability Criterion (SSC); Tactical Sustainability Design Guideline (TSG); Sustainability Compliance Index (SCI).
2. Identification of key performance indicators to measure the sustainability criteria. This step is supported by a database of more than 250 product-related leading Environmental Performance Indicators (EPIs), identified by means of a systematic literature review, and a guide to support their selection by companies based on life-cycle stages and environmental aspects (Issa et. al, 2015).

In summary, this research combines the SSC and EPIs as an approach to improve the applicability of the sustainability criteria and support sustainability guidance and assessment in the TRA matrix through TRLs 1-9.The suggested solution is tailored for the specific company but also potentially valuable for other companies working with TRL and TRA in the technology and product development. The integration of sustainability into the TRA matrix is described as a step-by-step approach going from an overall level to a more detailed level including concrete guidelines and indicators.

3 RESULT

3.1 TRL1- TRL4

TRLs 1 to 4 go from preparing the development program to building a basic working prototype. The *sustainability guidance* is suggested to be included as an individual topic in the TRA matrix, Figure 1.

	TRL 1	TRL 2	TRL 3	TRL 4
What do do:	Have leading sustainability criteria been identified?	What are the overall sustainability targets?	Have a material criticality assessment been conducted?	Have a first indication of sustainability challenges been identified?
Example of how to do this:	Identify leading sustainability criteria.	Define targets for each of the tactical design guidelines connected to the leading sustainabilty criteria.	Do a material criticality assessment, using the material criticality assessment method for alloys.	Do a SCI assessment for the leading criteria of the technolgis or different types of concept solutions.

Figure 1. Illustration of the sustainability guidance for TRL1-TRL4 at the case company

TRL1

The task at TRL1 is about *identifying leading sustainability criteria from the Sustainability Design Space*. At the case company, 7 out of 43 leading criteria were identified based on three selection characteristics: i) data and information availability for SCI judgement; ii) coverage of sustainability dimensions (social, environmental and economic/business perspectives); iii) aspects that affect the concept design directly or indirectly and that will be hard to change later on (or more costly) (Hallstedt and Isaksson, 2017).

So-called *leading criteria*, divided in SCI levels for each life-cycle phase from the Sustainability Design Space, represent the most important sustainability aspects that can be accomplished within the time-constrained early design situation (Hallstedt and Isaksson, 2017). Detailed information and data in the early technology and product development phases from suppliers are very difficult to get, e.g., data regarding usage of materials that contain or result in chemicals that are included in the REACH-candidate list (European Commission, 2006); and data regarding raw materials and chemicals and/or its manufacturing sites used that cause physical degradation of the environment. These types of sustainability issues can change and be improved later in a dialogue session with the suppliers. The leading criteria support the product design team in what to prioritize when doing a first sustainability assessment for guiding decisions and get guidance from using the connected tactical design guidelines. Later in the design process, more detailed analyses and down-selections need to be done even more. Like a spiral development the same question will come back again but on a more detailed level with more data and detailed information to seek, but for fewer alternatives (Unger et al., 2009).

TRL2

At TRL2, the product design team should *define targets for each of the tactical design guidelines connected to the leading sustainability criteria* to support the development and identification of the most promising solutions. The tactical design guidelines support development towards the related long-term SSC. The tactical design guidelines for the case company are presented in Figure 2.

DECISION ASPECTS CONCERNING PRODUCT LIFE CYCLE PHASES	TACTICAL DESIGN GUIDELINES
Raw materials: materials and chemicals that are used for the product components and/or its production.	Reduce (in %) risk materials for product components and/or its production.
Production: production by suppliers of sub-components & materials, as well as production of products at the own company.	Reduce (in %) emissions and scrap of metals (especially scarce metals) Reduce (%) emissions and waste products containing substances included in the SIN-list
Distribution: transportation of materials, substances and products connected to the company products and its production.	Reduce (in %) risk for unsafe transports of materials, substances and products
Use & Maintenance: activities and design that affect the sustainability impact during the usage phase.	Reduce (in %) product weight Reduce (in %) dB noise during the use and maintenance of the product
End of Life: activities and design that affect the sustainability impact during the end of life phase.	Increase (in %) of remanufacturability and recyclability of the product components

Figure 2. Tactical design guidelines for leading sustainability criteria at the case company

TRL3

At TRL3, analytical and experimental proofs of concepts are required and design-specific data, such as material screening, are requested. Therefore, *material criticality assessment from a sustainability perspective* will need to be conducted. For the case company, a method specifically relevant for alloys, which is divided in 3 steps, is used: i) identify potential critical elements based on availability and sustainability aspects for each alloy; ii) grade the level of criticality for each alloy using SCI; and iii) compare sustainability ranking of alternative alloys. See Hallstedt et al. (2016) and Hallstedt and Isaksson (2017) for more details.

TRL4

At TRL4 a basic prototype in a laboratory environment is expected and for a sustainability guidance, *an SCI assessment for the leading criteria of the different types of concepts solutions* should be conducted. This will give a first indication of their different sustainability challenges, which may result in a reduced number of concepts for TRL5. In Figure 3, an excerpt of the SCI for the case company (focused on material selection and production) is presented.

Material selection		Production	
9	No risk-materials used according to material criticality list.	9	**i)** Only recycled materials are used, with no metal emissions and all scrap metals are recycled into pure fractions. **ii)** No emissions and waste products from production sites (even at suppliers) contain substances in the SIN-list.
6	No alloys that includes conflict elements, or, high availability risk elements are included, but still includes elements with high anthropogenic flows compare to natural flows.	6	**i)**Recycled metals are used and over 50% of the scrap metals are recycled into pure fractions. **ii)**A phase out/substitution plan is followed for those chemicals/materials used that is included in the SIN-list.
3	No alloys that includes conflict elements are used but high availability risk elements are included.	3	**i)** Recycled metals are used in production, but it is not known to what extent there are emissions and scrap of metals from production. **ii)** There are no emissions and waste products from production sites that contain substances in the REACH-candidate list, but chemicals/materials included in the SIN-list occur.
1	Alloys that includes conflict elements and other risk elements.	1	**i)** No recycled materials are used and/or it is not known to what extent there are emissions and scrap metals from production. **ii)** There are emissions and waste products from production sites that contain substances in the REACH-candidate list.
0	Do not known if and what risk materials that are present in the alloys today	0	i) Do not know if and how much recycled materials that are used. Do not known the amount of emissions and scrap metals from production. ii)It is not known if there are emissions and waste products from production sites that contain substances in the REACH-candidate list

Figure 3. Excerpt of the Sustainability Compliance Index for the case company

3.2 TRL5 - TRL9

At TRL5 to TRL9, the prototype is further developed from testing in relevant and realistic conditions to industrialization and interactions with stakeholders and finally demonstrated technologies in normal operations. See Figure 4 for a schematic process of TRL5 to TRL9.

	TRL 5	TRL 6	TRL 7	TRL 8-9
What do do:	Have Environmental Performance Indicators been identified for the leading sustainability criteria?	Have a road map for sustainability improvements been developed?	Have comparisons of alternative solutions on product design and/or production been made from a sustainability perspective?	Have a discussion taken place with stakeholders to improve the sustainabilty performace considering the product's complete life cycle?
Example of how to do this:	Identify EPIs	Conduct SCI assessment for all sustainability criteria and life cycle phases. Use the tactical guidelines for the sustainability criteria in the design space for improvement suggestions and present in a road map for sustainability improvements.	Further detailed comparisons and selection between different alternatives should be verified with sustainabilty assessments, e.g. Sustainability Assessment and Value Evaluation (SAVE) analysis.	Have regular contacts and discussions with suppliers and stakeholders to find solutions to improve the sustainabilty performance considering the product's complete life cycle. Aim towards SCI3-9 for all criteria.

Figure 4. Illustration of the sustainability guidance for TRL5-TRL9 at the case company

TRL5

At TRL5, the sustainability guidance is to *use quantitative indicators to measure the leading sustainability criteria*, which can be identified by means of the EPIs database. The selected EPIs should be related to each of the leading sustainability criteria and can, in this early development stage, be used to compare alternative concepts from a sustainability perspective. The purpose of the sustainability guidance at TRL5 is to support the identification of the most optimal concepts from a sustainability perspective on a detailed level. The identification of potential EPIs to measure sustainability priorities was performed based on the first 3 steps of the 5-step selection process defined by Issa et al., (2015). The definition of priorities and objectives (Step 1) was carried out for the case company based on the identified leading sustainability criteria, by means of the SCI assessment and embraced the 5 priority areas for each life-cycle stage (incl. material selection, production, distribution, usage and maintenance, and end-of-life). Subsequently, the pre-selection of the EPIs was carried out (Step 2), using the classification criteria of the EPIs database (Issa et al., 2015). Table 2. summarizes the results obtained in Step 3, which dealt with the pre-selection of the EPIs from the database. While the table presents all possible alternatives, a selection of the most relevant EPIs should be performed. Due to the scope of this initial study, steps 4 and 5 were not yet implemented. It is expected that the further application of the proposed approach by the case company will drive the refinement and customization of the EPIs, as well as have their full implementation in the TRL assessments.

Table 2. Pre-selected EPIs for each leading sustainability criteria for the case company

Sustainability Criteria	EPIs	
Material Selection Life cycle: Pre-manufacturing Aspects: Hazardous Materials	Hazard Quotient	HQ is an indicator used in the risk assessment of toxic substances a product, which involves the type of toxic, exposure assessment and risk characterization.
	Variety of Hazardous Materials	This indicator measures the number of hazardous materials in the production process.
	Hazardous Materials Input Mass	This indicator measures the absolute mass of hazardous materials input in the production process.
	Amount of Restricted Materials	This indicator measures the absolute mass of all restricted materials used in production.
Production (i) Recycled materials Life cycle: Manufacturing and Design Aspects: Recycled materials	Recycled Material Fraction	This indicator measures the recycled material use relative to the total mass input in the manufacturing system.
	Recycled Solid Waste Mass Fraction	This indicator measures the recycled solid waste absolute mass relative to the total amount of solid waste generated.
Production (ii) Emissions and waste Life cycle: Manufacturing and Design Aspects: Solid Waste, Waste and Gaseous Emissions	Polluted Liquid Waste volume	This indicator measures the total volume of polluted liquid effluents produced by the company.
	Hazardous Sludge Volume	This indicator measures the generation of hazardous sludge volume during the manufacturing process.
	Specific Air Emissions per Substance	This indicator measures emissions of specific substances per year, such as SOx, NOx, particles, etc.
Distribution Life Cycle: Distribution & Packaging	-	not identified
Usage and maintenance i) weight and energy Life cycle: Use and maintenance Aspects: Select systems with energy-efficient operation and use stage	Energy Consumption during Use Phase	Amount of energy consumed in the use phase during the lifetime of a product
	Combustion Emissions	This indicator measures the total emissions from combustion in use stage.
	Energy consumption in standby mode	This indicator measures the energy consumption in standby mode.
	Energy Consumption during Use Improvement Ratio	This indicator measures the reduction in percentage of energy consumption during use phase.
Usage and maintenance ii) noise Life cycle: Use&maintenance Aspects: Energy loss	Noise	This indicator measures the noise emitted from the manufacturing process. The impact of the noise can be evaluated by the number of complaints of the neighbourhood.
End-of-life i) recycling Life cycle End-of-life Aspects: Adopting the Cascade Approach, Selecting Materials with the Most Efficient Recycling Technologies	Recyclable Materials in the product	This indicator measures the mass of recyclable in relation to the total mass of the product.
	Laminated or Compound Materials	Laminated or compound materials have limited potential for recycling. This indicator measures the mass of laminated materials or compounds in relation to the total weight of the product.
	Energy for Recycling	This indicator measures the energy required for recycling materials.
	Fraction of Recyclable Material	This indicator measures the volume fraction of recyclable material of a product by means the sum of the volumes of all the parts destined to recycling to the overall volume of the product.
	Recycling Performance	The recycling performance RP is related to the product's recyclability, according to the end-of-life options, or Recycling methods.
End-of-life ii) remanufacturing Life cycle: End-of-life Aspects: Facilitating Remanufacturing	Fraction for Re-manufacturing	This indicator measures the volume fraction of re-manufacturing of a product by means the sum of the volumes of all the parts destined to re-manufacturing to the overall volume of the product.
	Fraction of Parts to Remanufacture	This indicator estimates the percentage of product destined to remanufacture.

TRL6

At TRL6, a roadmap for sustainability improvements of the selected concept should be developed. At this stage, more information of the technology, its stakeholders, processes, etc., is known and *an SCI assessment for all sustainability criteria in the design space* is made for the selected concept. See examples of roadmap development based on SCI in Strömberg and Ramachandran (2014); and Jaghbeer and Motyka (2016). To decide about sustainability improvements, *support from the tactical design guideline* for all sustainablity criteria can be used.

TRL7
At TRL7, there might be some detailed comparisons that are still of interest and in these cases enough data for a *simplified life cycle assessment or similar tools* can be used. At the case company, detailed comparisons and selection between different alternatives are verified with a Sustainability Assessment and Value Evaluation (SAVE) method (Hallstedt et al., 2015). This method is used to build net present value scenarios based on a sustainability assessment.
TRL8-9
At TRL8 and TRL9, discussions and *continued improvements* at suppliers and other stakeholders are needed to find solutions to improve the sustainabilty performance, considering the product's complete life cycle. The minimum aim is to at least meet SCI3 for each criterion, which is a low but acceptable level compliant with current legislation in the area. However, most criteria should have a SCI6-9, which means that the product solution is moving strategically towards a more sustainable product.

4 CONCLUDING DISCUSSION

In this paper, we presented an approach that systematically includes sustainability, through different support tools, using a technology readiness assessment (TRA) approach for technology and product development.
This research combines the SSC and EPIs as an approach to improve the applicability of the sustainability criteria and support sustainability guidance and assessment in the TRA matrix, through the progression along TRLs 1-9. The outcomes from this process are new product-and process technologies that will become part of the company plattform and will be the base for new developed products expected to be produced and sold at the market for a long period of time (about 20-30 years).
The suggested approach aims at addressing the challenges of sustainability integration into the early phases of product and technology development in the following way:

- The strategic sustainability criteria represent the long-term perspective, whereas the tactical sustainability guidelines and the indicators represent the short-term perspective. The strategic long-term criteria are the ideal long-term sustainability targets and something to strive for. These are based on a rigorous definition of sustainability using overarching sustainability principles at the basis of a backcasting perspective (Broman and Robèrt, 2017; Missimer et al., 2017).
- Social sustainability aspects (e.g., work practices and adequate working conditions, diversity and equal opportunities, relations with the community, social policy compliance, consumer health and safety, and human rights) are as important as the ecological perspective. However, it is a weakness of the suggested approach that the social aspects are covered with less detail and at a less explicit level than the ecological aspects, due to a lower maturity of the social sustainability area.
- No expert is needed in order to apply it, which means that comprehensiveness is balanced with the ease of use in the day-to-day engineering working environment. Furthermore, the approach balances the engineer's desire for hard facts related to the value generated by sustainability assessments without being too simplistic and reducing the sustainability scope.

However, further testing and evaluation is needed to validate this approach. The suggested approach has been co-developed in collaboration with the case company, and is in the process of being tested in an actual technology development project to be adopted to the company language for implementation. The next steps of this research are related to the application of the proposed approach in other companies with a similar approach for technology development (i.e., with the use of TRLs) to test the robustness of the approach and enhance its generalization for application in diverse contexts.

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