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Exploration of simulation-driven support tools for sustainable product development

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Abstract

Global society is encountering many challenges such as climate change, resource depletion, etc., which comes with a set of challenges and opportunities for businesses. Applied research in operational tools and methods that support sustainable product- and service systems innovation, aims to strengthen businesses to overcome these challenges. In recent years, several tools and methods have been developed in the sustainable product development field with focus on modelling and digitalization. This paper explores how sustainability has been integrated in modelling and simulation, and presents results from a literature review with the purpose of highlighting opportunities and challenges in the field. Furthermore, an initial model-based engineering support toolbox (MBE) is presented, with focus on support tools for socio-ecological sustainability integration in the early product development stages.

Keywords: Sustainable product development; simulation-driven models; support tools; sustainable PSS

1. Introduction

Global society will encounter unprecedented challenges; climate change, resource depletion, chemical pollution and increasing social problems, which collectively represent the major problem of un-sustainability [1]. Those global effects come with a set of challenges and opportunities from a business perspective, such as increased material and energy prices, harsher legislations, etc. Methods and tools to deal with such situations are needed on strategic, tactical and operational levels inside the companies. However, practical methods and tools on the operational level, with purpose of increasing the industry's capability to mitigate and deal with the risk dimension of unsustainable solutions are limited today [2]. Applied research in operational tools and methods that support sustainable product development (SPD), (i.e. a strategic sustainability perspective is integrated and implemented into the early phases of the product innovation process, including life cycle thinking) aims to strengthen businesses to overcome this challenge, in addition to increasing the companies competitiveness. Several generic support tools have been developed for SPD, summarized in e.g., Salari and Bhuiyan [3], and Buchert et al. [4], which aim to support development teams in integrating sustainability in the early development stages and give guidance in their decisions. However, some challenges are pointed out for these methods: Combination and integration within the product development process; inclusion of a whole life cycle perspective; only a few is validated in companies; and, not based on a clear definition of what the sustainability dimensions mean. Furthermore, few support tools include a long-time perspective which makes it harder to take actions today for issues that might occur in the future while the solution is still operational [5].

It is complicated for companies to do SPD for new innovations for products, services or production methods in parallel of reaching economic targets [6]. The objective of SPD research area is to address the challenges mentioned above, in addition to challenges identified in Hallstedt [7], i.e.: How to identify which the most relevant sustainability aspects to

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consider; to what degree a concept performs in relation to a sustainable solution; and how profitability and values can be estimated for a longer time perspective and related to other parameters and requirements. Simulation methods and modelling could assist in better understanding of the sustainability consequences of a decision; by testing multiple interactions between environmental, social and economical sustainability aspects over long-time periods [22]. Even though simulation models have proven to be an efficient approach for product development decision making, it is still challenging to generate models that accurately: transfer qualitative sustainability data to quantitative data; and, compare quantitative sustainability variables against engineering data [21].

1.1 SPD and Product Service Systems (PSS)

PSS is a business model or a design approach that aims to develop functional solutions with both service and hardware dimensions. In general PSS solutions can form a platform to maximise the value of products and materials, and thereby also create circular economy strategies [15, 16, 46]. SPD is one of the approaches that can be combined with PSS to create more sustainable PSS innovations [14], as sustainable PSS has to be designed at an early stage, since it contributes to materials usage, energy consumption, etc. through the entire life cycle of a concept [47].

Despite the increasing interest in sustainable PSS innovation, the shift towards sustainable PSS remains unexplored in most companies [17]. Companies of tradition remain focused on cost efficiency and on solving incremental problems. However, this strategy can be combined with ambidextrous thinking where you balance today´s challenges with future potential solutions [18]. The challenges with a lot of information, data and requirements to consider in early stages of product development has made digitalization and big data a growing interest for companies [19]. Data mining techniques for big data can be used to enhance simulation models and to make model driven sustainable PSS innovation more efficient, as it can shorten development cycles and enhance multidisciplinary understanding early in the development phase [20, 21] before the solution is created. Many simulation approaches has been developed for PSS eco-design, such as the work presented by Chalal et al. [49] and Lee et al. [50].

1.2 Purpose

Extracted from the need to build more circular businesses and contribute to a more sustainable society, model-driven decision support for sustainable PSS solutions is of interest. The purpose of this paper is therefore firstly to explore how sustainability has been integrated in current model driven simulation approaches, and to present opportunities and challenges in the field from a literature review. Secondly, to present support tools for SPD in an initial model-based engineering support toolbox (MBE); and, thirdly to present an introductory approach for sustainability simulation support tool to be included in the MBE.

1.3 Paper disposition

This paper is organized as follows. Section 2 presents the research approach, afterwards section 3 illustrates the results of literature studies, opportunities and challenges in the field. Section 4 presents the MBE toolbox to be used in SPD. Followed by section 5, which presents an initial introductory approach for sustainability simulation support tool. Finally a concluding discussion closes the paper in section 6.

2. Research Approach

The research focus here is on SPD and simulation-driven design and model based development, using IT tools and softwares for analysis, modelling, simulation, visualization, and optimization. As mentioned previously there have been an increased development of support tools and methods for SPD. However, there are still few with a simulation-driven and model based approach that also address the challenges pointed out for SPD tools. Hallstedt et al. [23] suggested a modelling and simulation approach to assess sustainability and value consequences of PSS. However, further investigation with regards to sustainability and simulation integration is needed and therefore a literature review was performed to capture opportunities and challenges in the field.

Literature review was conducted based on an adapted version suggested by Biolchini et al. [24], consisting of four main steps:

- Questions formulation: Problem identification and selection of relevant keywords for the search.
- Sources selection: Strings and synonyms identified.
- Studies selection: Define the selection criteria e.g. journal/conference papers, language or time span. Results sorted by the inclusion criteria and analysed.
- Results summarization: Analysis and summarization of selected studies.

The research questions were formulated as: *"What are the main scientific publications regarding integration of sustainability in simulation-driven approaches for SPD?"* and *"What are the challenges and opportunities identified in this field?"*

The main key words used in the search were: sustainability and modelling; sustainability and simulation; social sustainability simulation; sustainability simulation product development; eco design simulation; environmental product development and simulation; and with special attention to synonyms. The search was conducted using a search platform that includes a set of databases, most articles were found through Science Direct, IEEE xplore and Scopus.

The selection criteria included peer reviewed conference and journal articles written in English between January 2005 and October 2016. Search results were evaluated for relevance (e.g., studies related to product development and manufacturing, had a life cycle perspective, included sustainability dimensions) by firstly reading the title, and then reading abstract and key words. If that was not sufficient for exclusion, then the introduction and conclusion were read. At this point the result yielded over 200 journal and conference papers. Identified papers used many simulation methods, so it was decided to add another criteria to limit the scope and therefore considered only papers using the main well known simulation methods:

- System Dynamics Modelling and Simulation (SDMS)
- Agent Based Modelling and Simulation (ABMS)
- Discrete Event Modelling and Simulation (DEMS)

Finally, if the previous criteria were not sufficient for exclusion then the full paper was read. The search resulted in 31 relevant papers, and the information was written in a worksheet with the following categories: title, year, used simulation method, validation of the study, dimensions of sustainability, key outcome, opportunities and challenges.

After identifying the opportunities and challenges an initial model-based engineering support toolbox (MBE) was presented, with focus on sustainability integration, to cover some of the identified gaps in the SPD field. Afterwards an introductory approach for sustainability simulation support tool to be included in the MBE was proposed. Both the tools/methods in MBE and the introductory approach for sustainability simulation support tool result from an on-going six year initiative with the industrial partner to explore SPD challenges [21]. Prescriptive research approach was followed, conducting an action based research, and working iteratively with the design team at the company in a similar way as described by Avison et al. [48]. The framework for strategic sustainable development (FSSD) was one of the common theoretical approaches used for these research studies in the initiative [10], FSSD was also used by other researchers in the area of SPD, e.g., Schöggl et al. [11]. In the FSSD, socio-ecological sustainability principles are used to define the overarching mechanisms to sustain the society and these are used together with a backcasting approach, which means imagining success in the future and then looking back to today in order to assess the present situation through the lens of this success definition and to explore ways to reach that success [12,13].

The MBE could support decisions when developing more sustainable PSS. So far, the tools and methods developed and presented here are support tools for SPD and aim to bridge identified gaps in the field. These tools and methods can be combined and complemented with other tools and methods for SPD in future work (see e.g. Buchert et al. [4] who analyzed and categorized several tools and methods for SPD), which is however beyond the scope of this paper. The tools and methods have been applied and validated in different cases and together with different industrial partners.

3. Results from the literature review

The papers reviewed in this article cover a wide range of topics in the area of simulation and modelling for sustainability. Therefore, analysis, challenges, and opportunities are synthesized from those publications and presented. Manufacturing received largest attention in simulating sustainability with DEMS. However, ABMS was the dominant method in simulating social sustainability, while hybrid modelling combining more than one of the main previously mentioned simulation methods was used in several papers. One hybrid model was developed by Fakhimi et al. [25] to assess social, ecological and economic sustainability of healthcare, assuming key process indicator/s for each sustainability dimensions. Another hybrid model was presented by Herrmann et al. [26] for optimizing energy flows in the production phase.

Environmental sustainability earned most attention in the literature, followed by economical sustainability, while social sustainability was covered in a very limited number of publications. Adewale Ajimotokan [27] investigated manufacturing safety through managing magnitude and risk factors of injuries. Boulonne et al. [28] introduced models covering ergonomics, in addition to other environmental indicators in manufacturing contexts.

The literature found in the field extensively focused on manufacturing contexts and energy consumption. Specifically, the area of sustainable manufacturing, where life cycle assessment (LCA) shortcomings such as ability to show sustainability implication over a long period of time were solved by integrating it with simulation models [29,30,31,32,33,34,35,36,37]. A limited number of authors took a full life cycle perspective when integrating sustainability into simulation models, for example Wang et al. [43] presented a hybrid simulation model covering the production, transportation, use and end of life phases of bottled water taking into consideration energy and global warming potential.

One essential step for modelling and simulation of sustainability is the definition of indicators to cover all three sustainability dimensions. However, the mechanism and reasons behind selecting those indicators were missing from the majority of reviewed papers. However, it is important to highlight those very few studies which clarified the indicators development process. Lee et al. [31] presented a sustainability simulation framework, which was further developed in 2014 [38]. The framework is based on the theoretical foundation of sustainable manufacturing principles, which is translated at a later stage into environmental, social and economical sustainability indicators. Another example is the framework developed by Zhao et al. [39] where the indicators were developed based on Institution of Chemical Engineers (IchemE) sustainability indicators and Global Reporting Initiative (GRI) indicators, to evaluate the implication they chave on energy use.

Mani, et al. [33] categorized the challenges of simulation and modelling for sustainability into: i) Technical barriers due to lack of: Datasets supporting simulation; reasoning and decision support; integration of sustainability indicators between simulation and data analysis tools; interpretation of life cycle issues; simulation model validation, ii) Psychological barriers: Adoption of new tools by experienced engineers; and, lack of management's trust on the outcome of these tools [33]. Moon [22] identified software capability limitations for simulation modelling as additional technical barriers, thus refining current and creating new softwares for sustainability is desired. It could be concluded from literature review that integrating sustainability in simulation tools for support in SPD is very limited, and thus there is a wide space for contribution. Most researchers focused on issues specific for manufacturing, some distribution and end of life, but none of the selected research studies in this review took a full life cycle perspective when assessing sustainability, i.e. starting from raw materials, production, distribution, use and maintenance, and finally disposal phase. Furthermore, a limited number of studies covered a full social, environmental, and economical sustainability with clear reasoning of indicators selection. The identified gaps are partially addressed by the approach presented in sections 4 and 5.

4. Model-based support toolbox towards a more sustainable PSS

The different SPD-tools and methods is here categorized according to their intended use by product development decision makers as seen in Fig. (1):

- Models for sustainability innovation
- Sustainability and value models
- Process optimization/product configuration

The relevant tools under each category are disposed under the three stages of SPD, which are scoping, emerging design, and concept development [45].

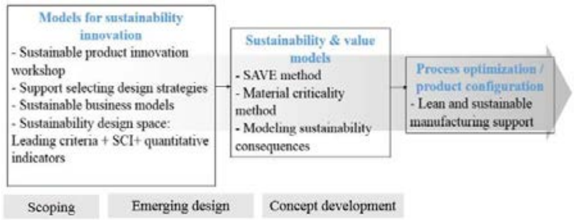

Fig.1. Sustainability integration in Model-based support toolbox

The MBE tools and methods are presented in more details in Table (1) illustrating the required data and results from using them. The sustainable product innovation workshop is used early in product development, utilizing guiding sustainability questions and a backcasting approach to identify the sustainability gaps of a concept [51].

França et al. [40] presented a qualitative approach for assessing the organization strategy, vision and business models with regards to sustainability, resulting in more sustainable business models. Hallstedt [7,8] developed the sustainability design space and Sustainability Compliance Index (SCI). Sustainability design space uncover the prioritized sustainability aspects for the company through all product life cycle phases. Sustainability Assessment and Value Evaluation (SAVE) utilizes a sustainability assessment to give guidance in creating scenarios with net present value results by comparing two manufacturing processes. In this way a long-time perspective was included and the sustainability parameters

Table.1. MBE toolbox illustration

Tool	Data characteristics	Required data	Purpose and results	Reference
Models for sustainability innovation				
Sustainable product innovation workshop	Qualitative	Organization vision, general knowledge and overview of current situation	-Sustainability gaps for current solution covering all life cycle phases. -Roadmap of actions towards a more sustainable solution	[51]
Support selecting design strategies	Qualitative	Depends on the company position in supply chain, and product life cycle span	A comparison between selected sustainable design strategies	[52]
Sustainable business models	Qualitative	Combination of the organization strategy, vision and business models	Various business models prototypes for strategic sustainability	[40]
Sustainability design space and Sustainability Compliance Index (SCI)	Qualitative	General Information about the sustainability related issues of the product over the different life cycle phases.	Defined SCI, concept development and visualization progress towards a more sustainable solution	[8]
Sustainability and value models				
SAVE	Qualitative and quantitative	-Legal internal/external environmental requirements -Technical requirements -Guided sustainability questions	-Identify sustainability hotspots and its complexity -Quantifying the value of the optional solutions	[44]
Material criticality method	Qualitative and quantitative	Alloy elements, weight %, database with material assessment methods.	-Identify potentially critical materials with focus on alloys -A four steps process for estimating vulnerability of products due to critical materials	[41]
Process optimization/ product configuration				
Lean and sustainable manufacturing support	Qualitative and quantitative	-Value Stream Map data -Sustainability assessment using Sustainability Life Cycle Analysis	A roadmap of actions towards a lean and sustainable production	[44]

were related to a monetary value [9]. The material criticality method is used to assess the criticality of alloy materials from a resource availability and sustainability perspective for a company's product development process. The method includes a material criticality list and sustainability compliance index score for advanced alloy compositions [41].

Though most tools and methods have been validated, still some challenges remain with regards to further verification for sensitivity and robustness for some models and others have to be validated in other industries. Finally, special attention should be given to check updates of the different databases. Furthermore, it is beneficial to integrate data mining in these methods, to make use of organizations sustainability data. However, a difficult problem would be to generate robust and accurate models based on small samples of data points defined by a large number of features [45].

5. Simulation-driven support tools for SPD

The next development step for sustainability integration in the MBE is to include sustainability simulation support tools, in order to deal with the complexity of sustainability data interactions [22] and to shorten development cycles and improve multidisciplinary understanding early in the development phase [20,21].

An introductory approach for sustainability simulation support tool included in the MBE support toolbox is under development based on the Sustainability Design Space. Leading sustainability criteria for each life cycle phase from the Sustainability Design Space is developed and selected to represent the most important sustainability aspects that can be accomplished within the time constrained early development situation [42]. The leading criteria support the product development team in what to prioritize when doing a first sustainability assessment for guiding decisions. The selection characteristics for a leading criterion are: i) possibility to find data and information for SCI judgement; ii) inclusion of all dimensions of sustainability, i.e., social perspective, environmental, and, economical perspective; iii) considerations of aspects that will affect the concept development directly or indirectly and that will be hard to change later on (or more costly). For each leading criterion quantitative indicators are created as seen in Table (2), which are to be used as inputs for simulation and modelling for sustainability.

Table.2. Leading criteria and indicators

Life cycle	Leading criteria highlights	Indicators
Raw materials	Critical materials	SCI score for alloys
Production	i) Recycled materials	% of materials used that are recycled input materials
	i) Scrap recyclability	Recycling rate of scrap (%)
	i) Risk of remanufacturing	Robustness index
	ii) Emissions, waste products and chemicals listed in REACH/IAEG lists.	Numbers of chemicals/hazardous materials used/generated in the production that are included in the REACH and IAEG lists.
	iii)Health and Safety	Number of injuries, risk of exposure, leakages
Distribution	Risk of being exposed to really dangerous substances even in small amounts or low concentrations	% of health risk due to exposure to really dangerous substances during distribution (per year)
Usage and maintenance	i) Optimized product weight	Weight reduction (for each component) in % compared to previous solution
	ii) No noise to the surroundings	Noise level reduction (for engine used in real life) in % compared to previous solution
End of life	All valuable materials/components are returned to the value chain for remanufacturing and recycling.	% of components that are possible to remanufacture and % of components that can be recycled

6. Concluding Discussions

The purpose of this paper was to review main publications in the area of sustainability simulation and modelling and identifying gaps and challenges in the field. In addition, the aim was to present an initial approach of MBE to cover for some of the identified gaps with seven different tools and methods. Result from literature review in section 3 showed that current tools and methods extensively focus on manufacturing, especially sustainable manufacturing, while less attention is given towards other life cycle phases such as: Raw material; distribution; use and maintenance; and, end of life. Another interesting finding was the limited focus on explaining the mechanism of selecting indicators. The tools in the presented model vary between having a quantitative and qualitative data, some even include a mix of both. The outcome of these tools range from providing a roadmap of actions to reach a more sustainable solution, generating sustainable business models, to identifying potential critical materials.

Several tools in this model considered a full life cycle thinking: The sustainability design space, SCI and leading criteria explaining the mechanism for prioritizing and selecting sustainability indicators based on the company´s needs, while avoiding suboptimization with regards to sustainability considerations and arbitrary selection of indicators. However, some tools in the model need further verification and validation. The presented tools and methods in the MBE are support tools for SPD, which could be of considerable importance in developing sustainable PSS solutions. Thus, in future research, complementary methods are to be investigated and included in the MBE to support sustainable PSS.

Further work will focus on developing the approach for sustainability simulation support tools included in the MBE. In addition, research will focus on integrating the developed indicators in simulation models, along with other engineering characteristic so as to give answers to the question: How to guide decisions for down-selection and exploration of emerging technologies and materials from a sustainability and value perspective?

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