Design for Sustainability in Manufacturing – Taxonomy and State-of-the-Art

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Abstract. To meet sustainability goals, manufacturing companies are faced with the challenge of using renewable resources as well as innovative processes to design and manufacture sustainable products. For this purpose, the Design for Sustainability (DfS) approach has been suggested. Since there is no uniform understanding of how such a concept should work and which methods should be applied within it, the paper is intended to provide an overview of existing approaches. Therefore, a taxonomy of DfS approaches is introduced to enable a systematic and differentiated analysis. Afterwards, a literature review is conducted and a comprehensive overview of DfS concepts is provided. This allows for uncovering research needs towards an established DfS approach.

Keywords: Design for Sustainability · Design for X · Sustainable Manufacturing

1 Introduction

Due to the depletion of existing resources and the increasing pollution of the environment, sustainability is more and more important. While there is still no uniform definition, the one of the Brundtland Report is often used. It defined sustainable development as meeting the needs of the present generation without compromising the needs of future generations [1]. Nowadays, the Triple Bottom Line is often referred to as a uniform conceptual element of sustainability: Sustainability refers to an environmental, an economic and a social dimension [2]. Against this background of increased striving for sustainability as well as the high relevance of the manufacturing sector for achieving the global sustainable development goals, the idea of sustainability in manufacturing should be considered in product design processes. This can be done by using the Design for Sustainability (DfS) approach. Although this quite novel approach is promising, a holistic concept with established methods for DfS still seems to be missing. Furthermore, an overview of the state-of-the-art of DfS does not exist. There is no substantiated knowledge answering the questions to what objects DfS refers, which tasks should be accomplished by DfS, and which way DfS is theoretically founded. This motivates the paper: By conducting a systematic literature review on DfS in the context of manufacturing such an overview

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should be given in order to enable further scientific development of the DfS approach and methods. To achieve this objective, relevant literature is identified and analyzed regarding various criteria that are defined in a DfS taxonomy.

2 Design for X and Design for Sustainability

Design for X (DfX) is an umbrella term representing a wide variety of approaches [3]. It can be noticed that there are more than 75 different DfX methods focusing on various aspects during the product design and manufacturing processes [4]. DfX approaches show two ways of interpreting the 'X' included in the term. On the one hand this 'X' represents a life cycle phase, e.g., manufacturing, service, or recycling. On the other hand it refers to a product property, e.g. cost, quality or safety [5]. This goes along with a large number of terms that can be used for the X resulting in various DfX concepts. They comprise DfS approaches striving for a systematic consideration of sustainability in design processes for products, processes, or resources.

Design for Sustainability is considered to have evolved from the Design for Environment (DfE) or Eco-Design approach [6]. Accordingly, great attention is paid to resource efficiency and sustainable consumption. However, a perfect product design concept should consider all three pillars of sustainability [7] in order to create sustainability-oriented innovations which aim at reducing the negative – and strengthen the positive – life cycle-related impacts of products within these three pillars [8]. Such a design approach can be understood as a DfS approach in a narrow sense. Nevertheless, another subset of all DfX approaches – those ones focusing on at least one sustainability dimension – can also contribute to reach sustainability targets (such as DfE for an environmental focus). They are seen as DfS approaches in a broader sense, here. In order to provide a significant overview, this study also includes such DfS approaches.

3 Taxonomy of Design for Sustainability Approaches

To present a significant picture of the state-of-the-art of the various DfS approaches existing in the manufacturing sector, a taxonomy is used. This taxonomy was derived from a taxonomy presented by Pecas et al. [9] who, amongst others, aim to study the state-of-the-art of life cycle engineering (LCE) – a similar group of concepts and methods – and intend to answer questions similar to those raised in the introduction.

The taxonomy (see Fig. 1) is structured in a hierarchical form. The first part – the **theory level** – considers the intended contribution of the analyzed publications. Here, their aim and content are characterized by answering the question "What is the intended type of contribution"? The second part of the taxonomy – the **design level** – is divided into two sub-levels. At the level of the **DfS activities**, the question "What is done by DfS" is to be investigated. In order to answer this question in a differentiated way, further sub-categories are considered. The target perspectives include the three dimensions of sustainability as well as aggregated target systems referring to two or all three dimensions. Another sub-level are the tasks that should be accomplished by DfS. Since the state-of-the-art of DfS approaches is to be investigated, it is to be expected that design (or engineering) is in the foreground. However, it is also conceivable that evaluation tasks are considered instead of or in addition to design (this is one result of the literature survey about LCE [9], p. 77). Furthermore, the basic DfX approaches suggested, and the methods applied within them are investigated. The second sub-level are the **reference objects**, with the question to be answered “To what objects does DfS refer?”. The reference objects can be structured in sub-categories too, here including alternatives (products, processes, or resources), life cycle phases and target figures.

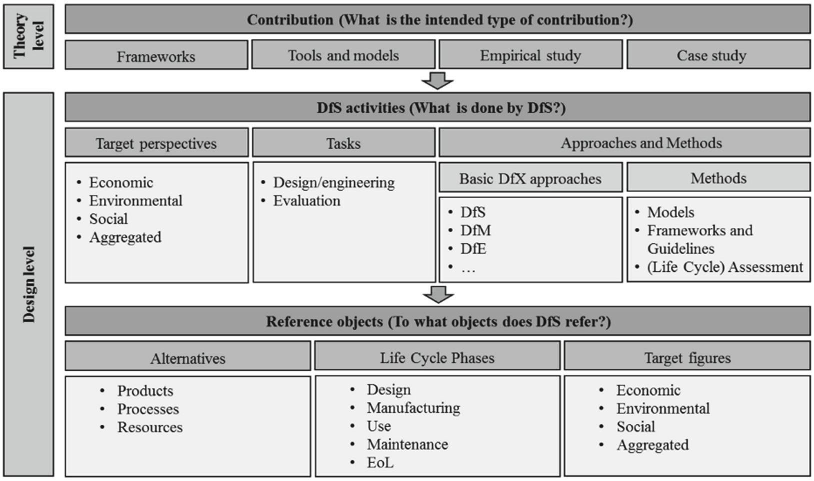

Fig. 1. Taxonomy

4 Methodology of Literature Review

For providing the intended state-of-the-art, firstly the relevant publications had to be identified. To find such articles, adequate keyword combinations had to be defined, and suitable databases had to be selected. The literature research was done by using four databases: EBSCO, ScienceDirect, Scopus and Web of Science. For searching in these databases, keywords were selected and connected with the Boolean operator ‘AND’ to create key word combinations. These keyword combinations can be classified into three parts. The first section represents the combination of the search term ‘Design for X’ with either ‘sustainab*’, ‘manufacturing’ or ‘production’. In the second section, ‘Design for Sustainab*’ is connected to ‘manufacturing’ or ‘production’. Finally, ‘Design for’ was linked to either ‘sustainab*’, ‘manufacturing’ or ‘production’ and additionally one of the three sustainability dimensions was added. Since a comprehensive overview of DfS in a narrow as well as in a broader sense was intended, the search not only focused on DfS (e.g., key word combination “‘Design for Sustainab*’ AND ‘manufacturing’”), but also on DfX methods that address individual sustainability dimensions (e.g., key word combination “‘Design for’ AND ‘production’ AND ‘environmen*’”). Afterwards, the resulting key word combinations were used for searching for results in the title of articles in the data bases. This initially allowed 205 results to be found after the duplicates were removed. By scanning the abstracts (133 articles excluded), checking the bibliometric scores (H-index higher than 80 or VHB ranking of at least C; 45 papers excluded) and carrying out an in-depth analysis (twelve articles excluded) a total of 190 articles could be identified as not relevant. As a result, 15 articles remain as the most relevant publications, whereof one only provides an overview of existing approaches in the form of a literature review, which therefore was excluded. Nevertheless, this article as well as the other ones were used to find additional relevant literature using the snowball principle. Thus, two other publications were identified as relevant, which are therefore included in the in-depth analysis of 16 articles using the taxonomy (see chapter 3). The procedure of the literature review is presented in Fig. 2.

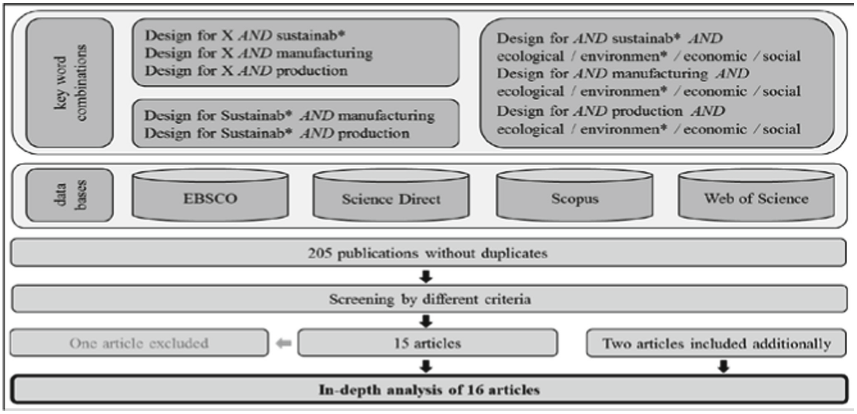

Fig. 2. Method of literature review

5 Results of Literature Review

For the in-depth analysis of the 16 selected articles, the DfS Taxonomy was applied. Consequently, they were firstly analyzed with regard to the intended **type of contribution**. Five articles represent purely methodological frameworks [3], [10–12] whereof one additionally focuses on behavioral aspects [7]. Seven other articles present methodological frameworks as well. Moreover, these frameworks are applied in case studies [8], [13–18]. Another publication combines a framework with a use case and a tool [19]. Of the remaining three publications, one is an empirical work [20], one is a methodical work suggesting a mathematical model [21] and one is a methodical work that presents a model and its application in a case study [22].

The **activities** sub-level follows in second place. Regarding the **target perspectives**, there are diverse results. Five articles focus exclusively on one sustainability dimension whereof three refer to the environmental perspective [10, 14, 16], and each one refers to the economic [22] as well as social dimension [13]. An economic and also environmental perspective is considered in four papers [17], [19–21]. These perspectives are supplemented by the social perspective in one paper [8]. Besides the individual evaluation of the sustainability perspectives, an aggregated view on the holistic sustainability can be found in five publications [3, 11, 12, 15, 18]. In addition to the three sustainability dimensions, an institutional perspective is included in another article [7]. Concluding, it is noticeable that more than half of the analyzed papers refer to only one or two sustainability dimensions. Just one paper considers all three sustainability dimensions separately. Another five publications show an aggregated view. This shows a non-uniform picture with a diverse target-orientation of the approaches.

Concerning the **tasks**, the design/engineering perspective is at least indirectly taken in all identified publications. This is inherent in the character of the 'Design for' approaches. Nevertheless, there are three papers in which the task of evaluation is focused [13, 19, 22]. Seven articles only focus on design/engineering [3, 7, 8, 10, 17, 20, 21] and six articles consider both design/engineering and evaluation [11, 12], [14]–[16], [18]. Concluding, the emphasis within the tasks is on designing and engineering of the reference object which is often supplemented by an evaluation.

A very diverse understanding of the considered DfS concepts can be seen regarding the **approaches and methods** suggested. As a basic **DfX approach**, DfE was used in four publications [10, 14, 16, 21]. Additionally, there are four articles that specifically refer to DfS [3, 7, 8, 12]. Furthermore, Design for Manufacture and Assembly (DfMA) was mentioned twice [18, 22] and Design for Recycling (DfR) [19] and Design for Remanufacture [20] were noted once each as basic methods. A further development of the Design for Manufacture, the so-called Design for Sustainable Manufacture (DfSM), was addressed in three publications [11, 15, 17]. The social dimension was once focused on by usage of Design for Social Sustainability (DfSS) [13].

Regarding the **methods** in detail, a framework for DfSS was presented that contains guidelines as well [13]. Moreover, a conceptual methodological framework which shows a six-step approach including a formula for DfSM was suggested [17]. Three articles present mathematical models [14, 15, 21]. Assessment procedures were mentioned in three articles. One article uses different indicators for assessment e.g., to determine manufacturing costs, energy consumption as well as personal health & safety [11], while another publication calculates a normalized score and therefore uses life cycle inventory and unit process modelling as a basis [18]. A third article presents a combination of life cycle assessment (LCA) with an adapted methodology for eco-design, the so-called eco-briefing [16]. Moreover, three paper present models, whereof one paper uses a software tool that is based on a multi-attribute decision making method [19], the second one is based on a computer-aided design model [22] and the third one contains different performance metrics [10]. Additionally, five publications are limited to theoretical considerations that provide starting points for methodological approaches. One presents ideas to include social impact categories in the LCA method [12], one presents a DfS taxonomy that combines various DfX approaches [3], and a third one presents four possible DfS approaches to innovation [8]. Moreover, one paper suggests guidelines for DfRe [20] and another one focuses on principles for DfS [7].

Regarding the **reference objects** within the design level of the taxonomy, nine papers focus on just one type of **alternative** (eight aim at products [7, 8, 12], [17]–[21] and one concentrates on processes [22]). Furthermore, three studies address two alternatives, whereof two studies focus on products and processes [3, 14] and one paper takes products and resources into account [16]. The other four studies include a third alternative. Three concentrate on products, processes, and resources [10, 11, 15] whereas one paper focuses on paradigms besides products and processes [13].

With regard to the considered **life cycle phases**, it is remarkable that the first group of DfX approaches explicitly bears one or more life cycle phases in its name (see chapter 2). However, this is not true for the remaining approaches. Therefore, all considered studies were examined in terms of their life cycle reference. The majority of papers analyzed (eleven out of 16) cover the entire life cycle (design, manufacture, use, maintenance, and EoL) [3, 7, 21, 8, 10, 12, 14, 15, 17, 19, 20], whereof two studies especially concentrate on the manufacturing and the EoL phase [20, 21]. One paper covers the product life cycle without the EoL phase [13]. Out of the remaining four papers, three focus on the planning and the manufacturing phases [11, 18, 22] and one takes the manufacturing phase exclusively into account [16].

Considering the **target figures**, there are five papers for which specific target figures are difficult or not at all to be named. These are the papers that are limited to theoretical considerations and do not suggest concrete methods [3, 7, 8, 12, 20]. However, there is one article that takes the *economic perspective* into account by using a method that leads to an optimized DfMA "decision" with lowest product manufacturing costs when considering engineering parameters as well [22]. Three papers present target figures that are related to the *environmental perspective*: an optimized overall utility [14], the environmental impact as target figure [16] and a focus on DfE principles that contain categorical as well as numerical characteristics [10]. The *social dimension* is addressed by just one paper [13] where 16 criteria are used as target figures. From the three papers referring to the *economic* and *environmental* perspective, the Global Recycling Index [19], a method that has an optimal DfE effort level as target figure [21], and a specific KPI (the life cycle commonality metrics) [17] are considered. The remaining three papers suggest an *aggregated* target figure considering all three *sustainability dimensions*: a Sustainability Index [15], a normalized score [18] and an acceptable sustainability level for products or processes [11]. Concluding, the analysis shows a variety of target figures are used even within the individual sustainability dimensions.

6 Conclusion

Based on a taxonomy presented, this paper analyzed the state-of-the-art of DfS concepts in the narrower and broader sense by doing a literature review. However, it should be noted that there are some methodological restrictions. First, the number of articles found is limited due to the key word combinations and databases used. In addition, the key words were searched exclusively in the titles of the paper. Moreover, the search was limited to DfS approaches related to manufacturing.

Regarding the analysis of existing DfS approaches, it can be noted that there are very few numbers (16) of papers that present DfS approaches with reference to manufacturing. Most of the approaches address only one or two of the sustainability dimensions. Articles that present a holistic method for DfS are clearly in the minority. It is particularly noteworthy that no two papers use the same methodology or the same target figures, even if papers refer to the DfS approach in a narrower sense. The great heterogeneity of the methods used implies that a state-of-the-art methodology does not exist. Furthermore, Life Cycle Costing as the accepted method for the evaluation of economic sustainability is not used in any of the papers analyzed. LCA as a state-of-the-art method for assessing environmental sustainability is used at least in some papers. These results are widely consistent with those of another literature review that focuses on the life cycle and sustainability-oriented assessment in the manufacturing sector [23].

As sustainability is becoming increasingly important, especially in the manufacturing sector, companies have to pay greater attention to using resource-saving processes and producing sustainable products. For enabling this, further studies should be directed towards developing a coherent and uniform methodology for DfS that takes the state-of-the-art of dimension-specific methods into account. Additionally, case studies should be conducted in order to validate and refine the methodology. By means of such a uniform methodology, it is then possible to compare the results of the case studies with each other and to derive significant conclusions regarding preferable alternatives.

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