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The role of modularity in sustainable design: A systematic review

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ABSTRACT

Modularity is a strategy recognized by the academia and the industry, and modular architecture is argued to play an important role in the development of sustainable products. The objective of this article is to explore the intersection between modularity and sustainable design from the perspective of the product life cycle. To achieve this objective, a systematic review was conducted and a total of 81 articles were selected and distributed in seven different categories of subjects: Life Cycle Assessment, Design for X, Green Modularization, Manufacture, Modularization Reviews, Supply Chain, and Usage. We identified in the literature that: (i) benefits are claimed in every life cycle phase (production, use, and disposal); (ii) academic research is mainly focused in the production phase and in projecting product disposal scenarios, offering a wide variety of methods and methodologies to modularize products with environmental concerns. However, modularity could also present limitations, and the realization of its benefits is partially influenced by user's decisions. Our conclusion points that, in spite of the association of modularity with environmental benefits, a better understanding of the entire life cycle of modular products and their environmental impact is needed to decide whether modularization is a suitable sustainable strategy or not.

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1. Introduction

Sustainable development has been highlighted as a central idea for our age (Sachs, 2014). It includes, in a general way, economic development, social inclusion, and environmental sustainability. However, sustainable consumption and production require the redesign of industrial practices, services, and infrastructures (Spangerberg et al., 2010). As a result, the focus in industry and legislation has changed from production processes to products and their life cycles. A product life cycle embraces all the activities from design to the end of life, including manufacture, assembly, testing, distribution, operation, services, reuse, remanufacturing, recycling and disposal (Gu and Sosale, 1999). The development of sustainable products is pushed by more demanding consumers and is the goal of emerging and integrated product policies, particularly in Europe (Hauschild et al., 2004). By making the manufacturer accountable for the entire life cycle of a product, regulations press companies to adequate their methods and are expected to pave the way towards environmental protection (Westkamper et al., 2000).

The product architecture has a significant effect on the whole product life cycle, hence affecting the sustainable characteristics of a product (Bonvoisin et al., 2016; Halstenberg et al., 2015). Modularity aims to break the product architecture into physically independent units (Newcomb et al., 1998), and a modular product architecture can facilitate the association of life cycle strategies with suitable product designs (Umeda et al., 2008). The idea behind a modular design is to allow the combination of distinct modules – through defined interfaces – to compose products. There are a variety of concepts on this subject, but according to Stewart and Yan (2008), the principal characteristics related to modularity are the structural independence, functional independence, minimization of interfaces and interactions with other modules and of external influences. Modularity facilitates upgrades, adaptations, modifications and product assembly and disassembly, it also increases product variety, enables economies of scale and reduces production time.

In light of its ability to influence the product life cycle and its sustainable characteristics, modularity has recently gained special attention in the field of sustainable design. Sustainable design aims to develop sustainable solutions, balancing private interests of the companies against environmental, economic and social concerns (Skerlos, 2015). As the environmental impact of a product is determined in the design stage (He and Gu, 2016; Jeswiet and Hauschild, 2005), sustainable design can help to meet consumer's requirements and integrate the environmental concern in the development of products. The terms Ecodesign, Green Design and Environmental Design are also used to describe the integration of environmental concerns in the product development (Jeswiet and Hauschild, 2005).

Literature generally associates modular design to environmental benefits. However, modularity has some limitations and might not be the most appropriate strategy for certain market segments. For example, products associated with status may not benefit from reuse/upgrade strategies allowed by modularization as the user values the act of owning a brand-new device. In these cases, user's decisions have a major effect on the environmental impact of a product (Lockton et al., 2008), limiting the benefits that can be achieved through modularity. Therefore, a better understanding of the environmental impact of each stage of the life cycle of a modular product, including the role of the user, is necessary to decide whether modularity is a suitable sustainable strategy and how to best take advantage of its strengths.

The objective of this paper is to explore the intersection between modularity and sustainable design from the perspective of the product life cycle through a systematic literature review. The contribution of this study can be summarized in two points. First, by reviewing research in published literature we present the benefits of modularization for sustainable design and devise categories of most recurrent subjects throughout the different life cycle stages; second, by presenting the limitations of modularity and highlighting research gaps in its relation with sustainable design, we advocate the importance of studying the entire life cycle of a product to ensure that modularity can enable sustainable design. These contributions can be used by researchers and practitioners to help to guide future developments of modularity for sustainable design.

2. Method

A systematic review was conducted to identify publications and topics relating modularity to the sustainable development of products. It included two main phases: selection and analysis. Selection comprised the gathering of a set of publications in the desired area, while the analysis comprised the critical examination of these publications to identify patterns and recurrent themes. As proposed by Kitchenham (2007), these two phases were executed in five steps: research question, search strategy, study selection, study quality assessment, and data extraction. This is not an exhaustive review of the research relating modularity and sustainable design. Instead, we aimed to assess the most recurrent themes relating these subjects and to explore their relation from the perspective of the product life cycle. In accordance with the aforementioned objective, our research question was: how modularity is associated with the development of sustainable products?

The Web of Science database was chosen because it includes highly cited scientific papers from journals that have impact factors in the Journal Citation Report (JCR). The search was conducted in the database with the following combination of keywords: (“modul* product*” OR “product* modul*” OR “modular design” OR modularity OR modularization) AND (“sustainable design” OR “sustainable product” OR “sustainable products” OR “eco-design” OR ecodesign OR “design for environment” OR “green design” OR “green product” OR “environmental design” OR “life cycle design” OR “product life cycle”).

The search terms associated with sustainable design were defined using the TerMine software results for two reviews (Chiu and Chu, 2012; Keoleian and Menerey, 1994). TerMine is a term extraction program that identifies the key terms in a text and produces a list ordered by their frequency and relevance (Frantzi et al., 2000). The Web of Science™ Core Collection search was conducted in topic (title, abstract and keywords) without restriction of time, in March 2017, and resulted in 145 papers.

All 145 papers were independently analyzed and only papers concerning modularity and sustainable design in the development of products were selected. Green building examples, papers regarding experiences with sustainability in formal education and