A framework for sustainability education for product developers

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INTRODUCTION

Striving towards sustainability, i.e. towards a reduced negative impact on the environment, human wellbeing, and global resources, is undoubtedly one of the major drivers in today's product development. Consequently, guidance for product developers has expanded over the decades from the arrival of new concepts, such as Design for Environment (DfE) and product specific eco-labels, to regulatory changes and ecological footprints [1], [2]. However, none of the presented eco-design concepts have gained dominance as a guidance for product development in companies [3]. Nevertheless, product developers and other engineers must now and will continue to contend with sustainability-related topics. The unfortunate current reality for them is that they often lack a fundamental understanding of these topics after graduation [4], [5]. Hence, there is a clear demand for the development of sustainability education for engineers. To address this concern, this study focuses on the education of product developers in particular.

The present study is framed by the literature on i) the integration of sustainability education in engineering or product development and ii) the practical integration of eco-design in the product development process. The literature on sustainability teaching for engineering introduces an array of descriptions for new courses on sustainability [6], [7], [8].

Furthermore, the approaches to integrate sustainability in existing courses are described from different perspectives. Some of the studies focus on the methods that can enhance learning sustainability, such as self-reflection [9], critiques by graduates [4], or problem-based learning [4], [9], [10], [11]. There have also been suggestions that a paradigm shift in engineering teaching from “predict and control” towards consideration and management of differing paradigms [12] along with a systematic approach for integrating sustainability in an engineering curriculum [13]. On the other hand, the practical integration of eco-design into the product development process presents studies on a specific eco-design tool integration, such as the 10 Golden Rules [14] or the MET Matrix [15]. Various eco-design tools have also been compared in terms of their practical usability [16]. Furthermore, attempts to co-integrate multiple eco-design tools studies in the product development process were made at both the general level [2], [17] and more specifically to find a suitable selection of eco-design tools for different stages of product development [18]. Previous research presents quite well the eco-design tools and methods for integrating sustainability in education. However, less attention has been directed towards the definition of learning goals particularly for the students in the field of product development.

This research elaborates on the present knowledge on both major approaches, namely the integration of sustainability in engineering and product development education and the integration of eco-design in the product development process. To facilitate this, we review the current literature focusing on developing a framework for learning goals on sustainability adapted for the needs of product development students. More specifically, this research aims to shed light on the interaction points between product development teaching and sustainability. In essence, product development forms the core of these studies, and sustainability is connected at the necessary points. Based on the literature review, a framework is presented for sustainability learning goals. This framework can be utilized by teachers of product development courses or programs to select and distribute sustainability learning goals for an individual course, for several courses, or across an entire study program of product development.

1. Study approach

The product development process developed by Ulrich and Eppinger [19] is the established representation of a product development process, which likewise serves as a model in product development teaching. The process steps are: i) Planning, including product planning, market analysis, generating product ideas, and developing design specifications; ii) Concept development, including developing concepts and evaluation, refining specifications, and selecting a concept; iii) System level design, including developing the construction structure, establishing the basic physical building blocks in terms of functions and interfaces; iv) Detail design, including preparing production, design for manufacturing; and v) Prototyping, testing, and refinement.

We chose to leave the production ramp-up outside the scope of this research. Naturally, the process steps are not always taken strictly in the described order nor do the sustainability questions appear solely in the phase-specific points; however, valid interaction points can be revealed when screening them.

Based on the need for sustainability knowledge, skills, and attitudes during the product development process, three research questions were formulated for reviewing each step of the product development process model: i) What are the major question(s) related to the product's negative impact on the environment, human wellbeing and/or global resources?; ii) What guidance tools are applicable for the decision making?; and iii) What are the knowledge, skills, and attitudes which are called for in the decision making? Reviewing the product development process from this perspective provided a set of key questions for each phase for the literature review:

- Planning: How to plan a sustainable product? What are the sustainable design specifications?
- Concept development: How to choose the best sustainable concept?
- System level design: How to integrate sustainability to the construction and physical building blocks of design?
- Detail design: How to integrate sustainability to production preparation and design for manufacturing?
- Testing and refinement: How to include sustainability in prototyping and testing?

2. Product development interaction with sustainability

2.1. How to plan a sustainable product? What are the sustainable design specifications?

At the planning stage, the framing for the whole product and its development process are defined. At this point, the sustainability considerations are more feasible to incorporate than at the latter stages [20]. At the planning stage, a holistic study on how to meet the user's needs has produced innovative immaterial solutions in the form of new business models [21]. Hence, the learning goals on sustainability here parallel the general product development learning goals; the holistic approach to user needs is crucial for both.

At the planning stage, no details on the product are available. Hence, the applicable sustainability guidance may remain at a general level. For this purpose, tens of eco-design tools are offered to guide the product developers to make general sustainable choices. For instance, Birch et al. (2012) list 22 tools, e.g. the 10 golden rules and Lifecycle design strategy wheel [3]. Consequently, the learning goal becomes a matter of acknowledging the availability of the various tools and being able to apply the selected tool(s). None of these aforementioned tools has gained an established position among companies. Instead, companies tend to apply their own databases and easy-to-use software tools for product analyses, manuals to help implement eco-design, simplified tailor-made tools, such as checklists, design rules, and protocols [22]. This guidance stems mostly from company image, current or forthcoming legislation, and customer requests [22]. Acknowledging the sources behind a company specific guidance is a relevant learning goal especially in cases where the company does not yet have its own product development guidance.

i) Company image and customer request

Building a company image and addressing customer requests are rooted in the same concern. Company image is increasingly built on the Global Reporting Initiative (GRI),

United Nations Global Compact (UN GC), or any one of over 40 systems/ indexes utilized in company communications [23]. Another concern in building a company image is directly linked to product marketing; the product specifications may demand compliance with an eco-label or an ecological claim [2]. Eco-label criteria are created and systematically developed by third party organizations, such as the Directorate-General for the Environment of the European Commission and Nordic Eco-labelling. These criteria include a multitude of perspectives on product life cycle impacts from material selection to energy consumption to production of emissions. These criteria can be considered as reliable sources of information despite the fact that the differing criteria do not provide an unambiguous recipe for “the best sustainable product”. Instead, it is often the one-dimensional slogans and claims which may be considered as unreliable. The claim may also be irrelevant in terms of the required improvement or may simply be spurious [24]. This kind of ambiguous marketing, i.e. greenwashing, is diminishing the trust of consumers in sustainability related marketing [24] [25]. Consequently, the learning goal is the critical attitude towards specifications and the information sources behind them.

ii) Legislation

There is a sizeable number of regulations and directives guiding product development and more on the horizon. They range from restrictions on materials and substances in products to product functioning, including energy consumption, and finally to emissions and waste generated by products and their production. In this respect, there is no need for decision making on applying binding legislation; it must be followed. In the case of emerging regulations, decisions must be made on timing. There is evidence that pursuing implementation of emerging regulations at an early stage is feasible from an economic point of view [21]. In an established company with established product types, the regulations are an evident source of guidance. However, in a new company or with a new technology, there is a need to study the regulatory framework. The learning goal here is to acknowledge the regulatory framework and sources for further information. Furthermore, the first adapter attitude must be enhanced in terms of implementing the future legislation.

Finally, the product developer should aim at obtaining and implementing the most reliable specifications for a new product either internally from the company guidance or from reliable external sources.

2.2. How to choose the best sustainable concept?

At the concept development stage, the specifications are refined, and from a sustainable development perspective, the guidance remains the same as in the planning stage. Consequently, this stage does not bring new learning goals in addition to the previously mentioned ones.

2.3. How to integrate sustainability in construction and in physical building blocks design?

The structure of physical products calls for material choice. Despite the strong negative and positive reputations of different materials, there is no clear way of ranking the materials according to their sustainability [26]. In addition to concepts, such as Design for Material Conservation (DfMC) or Design for Recycling (DfR) [27], software (SW) tools are also available for comparing the choices in material properties. For instance, the Cambridge Engineering Selector (CES) is a material selection SW, which provides

information on the environmental performance of the products [28]. Moreover, certain design tools, such as SolidWorks, calculates environmental factors on made designs [29]. An awareness of the available tools and concepts and an ability to use the environmental performance calculation functionalities is a key learning goal here.

It may seem obvious that material consumption is always optimized carefully. However, this is not the case today, largely due to the low proportion of material costs in comparison with the total costs [30]. And yet, material depletion remains a global concern [30]. This depletion will lead to higher material prices and to the increasing importance of material efficiency in development. Hence, for future product developers, the optimization of the material usage is increasingly important, not only from a sustainability point of view but also as a basic element of the development of a competitive product.

2.4. Detail design: Design for manufacturing

In the detail design stage, the product composition is planned according to the production equipment available. At this step, the question related to the sustainability is: How to combine the manufacturing requirements with the requirements of disassembly at the end of the life of the product? For this purpose, there is also specific guidance under titles, such as Design for Remanufacture, Reuse & Recycling (Df3R), and Design for Disassembly (DfD) [1]. These concepts are worth bearing in mind as growing pressure is put on the management of the end of the life cycle; recyclability and waste management.

2.5. How to include sustainability in testing and prototyping?

In the testing and prototyping stage, the product information exists, and the information for a full Life Cycle Assessment (LCA) is widely available. LCA is a comprehensive compilation of the product's negative impacts on the environment and global resources along the entire life cycle from raw material production to product manufacturing and usage to waste [28]. Its usability in decision making during the product development process is limited due to the extensive time requirement of 2–3 months and to the lack of necessary information [28]. Instead, in the late stages of the product development process, when the information becomes available, changes are not likely to take place [20]. However, putting effort into the full product LCA at this late stage in the process will serve future product development in the company. The consequential learning goal becomes an understanding of the concept of LCA and an ability to evaluate information achieved by an LCA.

At this point, the general learning goals would focus on the reflection on the attempts made towards sustainability during the product development process; on choices in the specifications; on the material choice and efficiency; and on design for production. The reflection on these attempts are worthwhile in both cases, if the attempt was successfully accomplished or not. As the regulations are continually tightening and new ones emerging, the voluntary guidance today may turn out to be binding regulation tomorrow. In these cases, the gathered information on the challenges in the implementation of a former guidance — i.e. the present regulation — are a worthy resource for future product development. Here, the learning goal becomes the realization that the ever more demanding regulatory network is a present development paradigm with an aim at proactive actions. Furthermore, the mindset for reflection must be developed on the process decision.

2.6. Framework for sustainable product development teaching

What kind of framework for learning goals for sustainability in product development studies can be drawn from the literature review above? Which knowledge, skills, and attitudes on sustainability are required during the various phases of product development? We have summarized the learning requirements from the above review of the product development process in a framework in Table 1.

Table 1. Framework for learning goals for sustainability in product development

Stage: Tools, material and concepts available	Knowledge	Skills	Attitudes
Planning: Eco design concepts and instructions	Distinguishing the different sources for the guidance for the specifications; regulations, eco-labels, CSR, and green marketing.	Holistic approach in user needs Seeking for reliable, up-to-date sustainability related guidance concerning the product to be developed. Realizing the continually growing regulatory and voluntary guidance towards sustainability as a tightening source for product development specifications.	Aiming at implementation of the best applicable sustainability guidance for product development specifications.
Concept development	as in planning	as in planning	as in planning
System level design; Material efficiency instructions and concepts Material selection software Environmental calculation functions in design SW	Acknowledging material sustainability functionalities in the material choice and design tools Being aware of concepts available for material choice such as DfME and DfR	Being able to utilize the environmental impact comparison tools and material optimization SW tools as a part of material selection.	Aim at taking material sustainability into account in the development. Considering material efficiency as a necessity in the future and including it in one's own product development practice.
Detail design; Design for recycling / dismantling instructions	Acknowledging guidance available for design for recycling or for disassembly		Bearing in mind the end of the product life cycle already when developing it
Testing and refinement; LCA on the product	Understanding the concept of LCA		Aim at reflection on the product development decisions made during the process to implement (or not) more sustainable solutions

3. Conclusions

The review of the literature compared to the phases of the product development process produced a comprehensive framework for learning goals in sustainability in product development studies, where the multitude of sustainability tools and guidance is tied directly to the natural contact point in the product development process. To summarize these goals, students should acknowledge the binding and voluntary guidance tools available and aim to critically choose and apply the relevant one(s). Whether the selected tool is implemented or not in the final product, the attempt to reflect on the reasons for the implementation or lack thereof needs to be conducted in order to help future projects. The importance of reflection must be emphasized by underlining the current trend in which the present voluntary guidance often leads into future legislation. Furthermore, at the end of the product development process, the available information permits the conducting of a full LCA, which also serves the needs of subsequent product development. Some of the learning goals related to sustainability parallel those of product development in general. In particular, a holistic, user-centered approach when defining the product specifications features prominently in both. Moreover, for the future product developer, material efficiency is not just a sustainability related topic, but it is also an approach for making competitive products in an increasingly resource intensive market.

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