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Design and manufacturing of a sustainable pedelec

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Abstract

To facilitate the transition towards sustainable manufacturing, current practices and mechanisms for value creation need to be reconsidered along the whole product lifecycle. However, academic research on sustainability is still bound to narrow fields of applications. In this study, a multi-disciplinary research project is presented that focuses on the development of a sustainable pedal electric cycle (Pedelec) from a first idea to a ready-to-use prototype. The results of the project show how different scientific approaches for bottom-up improvement can be applied together in a concrete case. A holistic view on the product lifecycle proved as a meaningful framework for that purpose.

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*Keywords:*Sustainable design; sustainable manufacturing; sustainable mobility.

1. Introduction

Nearly three decades after the publication of the Brundlandt report *Our Common Future* [1], progress regarding the implementation of sustainable development is still slow. The worldwide emitted anthropogenic greenhouse gas (GHG) emissions, for example, raised since 1990 by almost 30% to 49 Gigatons in 2010 [2]. Further threads to sustainable development, such as rapid urbanization or limited access to energy supply, have been named [3].

The manufacturing sector, as a major driver for resource consumption and environmental pollution, could contribute to sustainability, due to a considerable untapped improvement potential. Nevertheless, producing companies are still hesitant to revise their activities towards resource efficiency and social responsibility. Egilmez et al. (2013), for instance, showed that most US manufacturing companies are in fact eco-inefficient [4]. Garetti (2012) concludes in this context that: "New types of products, operations and organisation models will be needed to comply with the new constraints and the new objectives coming from the objective of sustainable manufacturing" [5].

There is already a large amount of publications in the field of sustainable design and manufacturing that focus on improving processes, providing assistance (e.g. by design methods) or building up a theoretical foundation for further research. However, due to the wide scope and the interdisciplinary nature of the research field it becomes increasingly intransparent for practitioners and decision makers to determine which types of methodological guidance are available and where those approaches can be applied in value creation. Furthermore, a holistic view of sustainable manufacturing is often demanded but rarely implemented. Researchers still tend to produce isolated solutions without considering the practical constraints of value creation or other

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research fields. Therefore, the following research questions shall be answered in this publication:

I. What are examples for implementing sustainability principles in different areas of sustainable value creation?
II. How can these approaches be combined and applied on one specific test-case? What are the benefits & drawbacks?

2. Sustainable manufacturing

Sustainability as one of the latest paradigms in manufacturing development refers to meeting human needs without overburdening nature or the fulfilment of needs of future generations. Sustainability can be understood in three dimensions covering economic, environmental and social issues [1, 6].

Economic improvement may be achieved in different areas of human living without increasing physical resource consumption, e.g. by increasing resource efficiency. For the environmental dimension in some cases mitigation of environmental pollution may be implemented due to increased recycling rates or usage of renewable resources. However, this approach must not hold true in any case.

On the social dimension, health and accessibility to resources is important, but also education may play an important role, when restructuring value systems [7].

Sustainable manufacturing is a paradigm which points towards new solutions for implementation of sustainability principles into value creation. Hence, it is a broad research area with many individual aspects addressed. Integrated approaches to sustainable manufacturing are rare. Thus, this study presents an attempt to approach this challenge.

3. Methodology

In order to answer the questions which were raised above, eight research projects within the Collaborative Research Centre (CRC) 1026 "Sustainable Manufacturing – Shaping Global Value Creation"* contributed to this study. The CRC 1026 is an inter-disciplinary science cluster consisting of seventeen sub-projects in the fields of manufacturing, design, economics, environmental and sustainable engineering and mathematics.

The main theme of the CRC 1026 is to show how sustainable value creation is superior to traditional means of design & manufacturing in ensuring economic wealth, environmental integrity and quality of life. These fields have been addressed by three project areas covering strategy development, new production technologies as well as principles, methods and tools for qualification.

In the following chapter a case study is introduced, which describes the interdisciplinary process of designing and manufacturing a pedal electric cycle or pedelec. The Smart Urban Wheeler (SUW) functions as an example and test case to combine the following research topics: Strategic planning using scenario technique, product development, automation in assembly, sustainability assessment, manufacturing & end of life planning as well as business process/ & business model design. All of the eight selected projects search ways for improving sustainability in their area of expertise. The study was motivated by practical application tests for achieved research results. As a surplus the researchers worked together in a team and therefore took into account the respective approaches of the other participants. Regular meetings were used to monitor the project progress and discuss important decisions. The success of the project was constantly monitored with Life Cycle Sustainability Assessment. As a basis for relative comparison an existing pedelec and a small passenger car was analysed.

As a framework for structuring the respective research approaches, the SUW´s lifecycle stages were chosen. Fig. 1 presents an overview of the life cycle phases covered. It depicts how from a future projection, specific functions have to be migrated into product design. Information flows from product design over to process design and onwards through manufacturing all the way to end of life (EoL). The conversion of raw materials starts at manufacturing and the objective is to maintain a perpetual flow of material in cycles. Chapter 4 will provide a more detailed description of the different phases (i.e. product design, process design, manufacturing, assembly and EoL).

After a motivation for the field of urban mobility every lifecycle stage is explained by a brief introduction of the applied research approach and an outline of respective contribution to the SUW (for more detailed information the interested reader is kindly referred to the references). After that the outcome of the project is presented and main findings of the process and their implication to value creation in general, are elaborated.

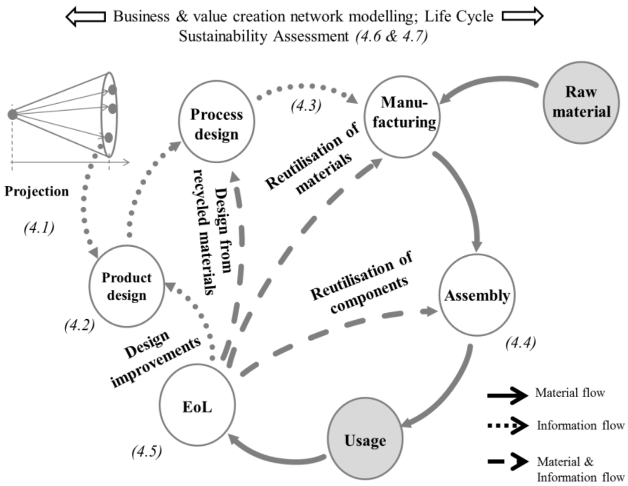

Fig. 1: Overview of the life cycle phases covered by the pedelec development

* www.sustainable-manufacturing.net

4. Case Study - Mobility and the "Smart Urban Wheeler"

Mobility, as a major human demand, is currently dominated by fossil-fuel based means of transportation. Cycling as a form of non-motorized transportation is ranging from less than one percent (e.g. Cagliary, Italy, 2001) to more than 30% (e.g. Groningen, The Netherlands, 2009) of the modal share [8]. However, there is a strong increase in activities dealing with bike mobility especially in urban areas [9]. Creutzig et al. point out that certain scenarios for decarburization policies in urban transportation could change the modal share in favour for non-motorized transportation. In particular, for smaller cities with less than half a million inhabitants a modal share of bicycles of more than 50% could be possible until 2040 [10]. Another development of the past years is the increasing diffusion of electrically assisted bi-and tricycles, so called pedal electric cycles or pedelecs. In 2006 more than 14 million two-wheeled pedelecs were sold in China what equals the amount of sold gasoline-powered two-wheelers [11].

In order to utilize these structural changes for sustainable development it can be worthwhile to rethink current industrial practices of bicycle design and manufacturing. Therefore, within the CRC 1026 project a pedelec (more precisely a triplec) has been developed under consideration of new technologies, concepts and methods.

4.1. Strategic product planning regarding future frame conditions

In order to develop sustainable products, the three sustainability dimensions as well as the future boundary conditions of the application fields have to be taken into account. Therefore, an integrated methodology to derive requirements for sustainable products based on scenario technique has been developed.

To address the use case of the SUW, three surrounding field scenarios for the future of bicycle mobility in Berlin have been developed. These scenarios incorporate factors, like the overall economic development, infrastructure investments and societal changes, specifically regarding mobility preferences. In a next step, the conceptual mobility needs have been transferred into functions, such as energy conversion and transport of persons and goods. Based on the product´s function, a broad variety of available technologies has been selected for further evaluation processes. Consecutively, validations of the technical compatibility between the different elements and a sustainability screening have been performed. As a result, three bicycle concepts, one for each surrounding field scenario, have been developed. The focus has been set on the scenario, which represents rising economic growth, larger demand for bicycles and therefore better bicycle infrastructure. The resulting requirements for the SUW combine improved ergonomics with high functionality and multi-person transportation. Furthermore, a high performance battery is used plus additional charging options such as solar panels and energy recovery dampers, an automatic transmission and connected communication technologies for smartphones [12]. The developed concept defines the basis for the following phases of the product creation process.

4.2. Product development

Product properties and characteristics, which are primarily defined in product design, can be considered as determinants for sustainability-impacts which occur in subsequent lifecycle stages. The diverse interrelations of product properties and lifecycle impacts are difficult to foresee, even for design experts. Furthermore, trade-off decisions between the sustainability dimensions are often necessary. Addressing this challenge, an IT-based assistance system has been developed which shall enable product designers to create more sustainable products.

Depending on the design target, type of product and further criteria the user chooses sequential and parallel combinations of design methods from the related database according to defined milestones in the product creation process (see [13]). The SUW development in particular has been supported by methodological guidance in requirement analysis as well as in the conceptual- and embodiment design phases. Within the requirement analysis, the desired product features and design targets defined in product planning (see previous chapter) were adopted and analysed. In order to systematically search for further improvement potential by analysis of existing products, codesign guidelines and *Life Cycle Sustainability Assessment (LCSA, see chapter 4.6.1)* were applied. Different types of two- and three-wheeled pedelecs served as a reference for that purpose [14].

Within the conceptual design process, multiple options for the materials and various manufacturing options of the frame were compared by an ontology-based multi-criterial approach leading to steel as the most preferred option (see [15]).

Furthermore, different means for decreasing energy consumption in the use phase (charging while standing & recuperation of braking energy) and the use of alternative energy sources (solar panel) were seen as beneficial. Improved ergonomics of the seating arrangement as well as an advanced concept for user´s interaction were also considered as design options to enhance the user's comfort and to provide additional information about energy, health and correct handling/maintenance of the bike.

Within embodiment design, the SUW (see Fig. 2) was modularized in order to adapt the product to different usage scenarios as well as to improve resource efficiency and economies of scale (different configurations for the gear as well as for the rack have been developed).

4.3. Process Design & Manufacturing

Subsequently to the product design different process chains with varying sustainability performance compete for manufacturing and assembly of the SUW. Therefore, new approaches for selecting the most beneficial option are necessary.

For that purpose information provided by the product development phase is used, like schemes, bills of material and design requirements. This information contains material, shape, geometry, number and type of the different

components. Based on this information, combinations of value creation factors (product, process, equipment, organisation and human) are specified in order to be able to establish adequate means to meet requirements from product development.
Assembly and manufacturing procedural charts are created. The information collected for that purpose covers the input and output shape, required manufacturing processes and the sequence of processes to be conducted [16]. Alternative options were generated for several components depending on necessary equipment, production location and production process. Such alternative options enable interlink to different sustainability objectives, e.g. reduction of environmental burdens through proper material selection, creation of adaptive workplaces in order to maintain a high level of ergonomics or optimisation of cost-benefits-ratios.

4.4. Assembly

The parts produced in the previous steps have to be combined in an assembly process in order to obtain the final product. The assembly of the SUW includes these processes: the assembly of the electrically driven bicycle hub (E-Hub), the assembly of the wheels and the final assembly of further components. Due to high complexity and number of product variations, the workforce in many companies has to adapt to changes in production processes almost daily [17]. Competent workers who are able to continually adapt to and perform under new and changing circumstances are therefore essential. The resulting effort to constantly train such workers is high and challenging. Thus, tools enabling cost efficient worker qualification are needed. Therefore, an assistance system [18] has been developed to support the worker in learning new manufacturing processes. The system consists of a Microsoft Kinect low cost 3D sensor and software components to recognize the 3D position of the worker's hands and the corresponding work step in process. The system creates intuitive, language independent and interactive work instructions through simple demonstration of the new process by an expert. Using the work instructions, the system supports the learner by detecting work sequence errors. With the information gathered, the system also measures the user's working and learning performance using methods-time-measurement (MTM) standards and adapts the learning material in accordance. The solution presented tackles the challenge of qualification and offers adaptive guidance and learning support for workers in the assembly of the SUW components.

4.5. End-of-life strategies

Material resources of many substances such as metals, minerals, gases and oils are currently exploited at a greater pace than what can be recovered through material recycling. The waste framework directive of the European Commission specifies the hierarchy of waste from the least favourite option to the most favourite option (landfilling, energy recovery, recycling, reuse/remanufacturing, minimisation and prevention). It promotes the reduction of generated waste and aims at a net decrease in harvested material resources [19]. Minimisation and prevention can only be regarded during the product development stage, and thus end-of-life (EoL) strategies within this context must address it. Such activities go beyond traditional thinking and require identification of new approaches for materials used in products.

Moreover, planned end-of-life strategies aim to recover materials according to their highest embedded value from the SUW. The bill of material, procedural drawings and engineering drawings has been reviewed. Parts have been categorized according to remaining value, possibility of reuse, remanufacturing or reconditioning, recycling, energy recovery, incineration or landfilling. Plans have been made to reintroduce the materials back into material cycles and, thereby, decreasing the need for newly harvested materials.

4.6. Life Cycle Sustainability Assessment

To ensure a sustainable product development, life cycle based methods can be helpful to assess sustainable impacts of products. Therefore, the life cycle sustainability assessment (LCSA) framework serves as a good basis to address the three pillars of sustainability (environment, economy and society).

LCSA is a retrospective method assessing a product´s performance via life cycle assessment (LCA), social life cycle assessment (SLCA) and life cycle costing (LCC). It assesses the complete life cycle of a product from raw material production through manufacturing and use until the end of life [20]. The measurement of impacts concerning the environmental dimension of sustainability is the most advanced method within the LCSA framework.

The LCSA framework has been applied on bike and pedelec cases and recently on the SUW covering all stages of the life cycle from production via the use-phase to the end-of-life [13, 14].

The findings served as a starting point for the sustainable product development (see chapter 4.2), as hotspots could be identified for all three dimensions offering possible pathways for optimization. Furthermore, the LCA results e.g. indicated a strong influence of the production and use-phase and have been reviewed in detail. Especially for the SUW, detailed material assessments have been performed to ensure the best solution for the frame material of the triplec. In this context trade-offs, as the result for different aspects considered (e.g. technical performance vs. environmental benefits) had to be elaborated. Materials considered are steel, aluminium, and titanium. Moreover, assessments for different maintenance scenarios have been performed. Further steps are planned addressing the EoL scenarios, which will be part of the bicycle recycling scenario development.

4.7. Business model design and value creation network modelling

An integrated task regarding the design and manufacturing of the SUW is the instantiation of a business case and the classification of a value creation network. The business model was developed on basis of the scenario introduced in chapter 4.1. A sharing concept was seen as most suitable as the baseline for the business model. This design can contribute to the overall sustainability of the SUW because utilization and product lifetime (due to correct maintenance) of the SUW are increased.

In order to account for the sustainability impact of value creation networks, an inter-organisational process modelling approach is followed. The collaboration of organisations, driven by cooperation and competition and taking into account multiple legislative or stakeholder requirements, is modelled within and across organisational boundaries. The enterprise model is used in this context as a common backbone for the representation of an enterprise regarding structure, activities, processes, information, resources, human beings, behaviour, objectives and constraints [21]. The value creation network has been created by combining several enterprise models of part manufacturers for the SUW as well as logistic providers and an assembling enterprise. The approach of multi-perspective [22] modelling allows for connecting the individual sustainability objectives and the associated indicators within one integrated model. For the definition of model elements (product, order, resource and action) related sustainability objectives and key performance indicators across the value creation network provide a basis for the collaboration as well as the assessment, management and reporting of the individual and combined sustainability performance represented in multi-perspective views [23].

4.8 Outcome

One of the first major challenges of the SUW case was to determine what a sustainable product is and how this abstract goal can be operationalized. Since there was no consensus found in absolute terms the concept of “Pareto sustainability” was applied as a working definition. Based on the triple bottom-line a more sustainable product or process can be achieved if at least one sustainability dimension is improved without compromising other dimensions. This principle was complemented with quantitative data from life cycle sustainability assessment for product concepts, pedelec parts and production processes.

As the work on the SUW begun the involved project teams started to define their ways of collaboration by specifying in- & outputs of their research approaches. After that the teams were able to identify synergies. The developed business model for example provided participating teams with a set of constraints which simplified the definition of commonly used assumptions (e.g. the product lifetime, which is important for design and assessment). Some projects were even able to establish “symbiotic” relationships since their research complemented well thematically and in terms of synergies in laboratory equipment. Two projects in particular (ergonomics and qualification in assembly) shared workplaces and application examples (e.g. assembly of pedelec wheels and motors).

In order to steer the project progress all important design decisions and their consequences on subsequent lifecycle stages were discussed in regular meetings. Having all stakeholders from the different lifecycle phases on one table proved as a beneficial instrument for implementing sustainability targets in the SUW development. Furthermore, benefits and obstacles of the respective methods and tools developed in the research projects could be evaluated on a practical example. For example not all requirements of strategic product planning could be implemented due to missing consistency with design methods used in product development (e.g. there were discussions about the pros and cons of modularity).

It was also possible to identify potential for interdisciplinary research within the collaboration process. One gap which was identified is the missing link between Sustainable Product Development and ergonomics in assembly processes for example. Several other links were revealed that will form the basis for future work.

The question whether the SUW is more sustainable than existing alternatives cannot be fully clarified at this point, since the project is still ongoing. Fig. 2 shows the planned (and partially implemented) features along the product lifecycle, which are results of the instantiated approaches of involved research projects. A first prototype is available, which already incorporates the majority of these factors for sustainability improvement. There are also methodological challenges to overcome for assessment. The compatibility of products with different functionality is challenging (e.g. full rain protection against partial protection). Furthermore, the availability of product-oriented indicators for social sustainability is still low. Ergonomics and safety could be measures for human health in production and the usage phase. However, at this moment there are missing concepts for quantification. The evaluation of cost is also a problem, since cost for a prototype cannot be compared to serial production. Assumptions need to be derived from the business model.

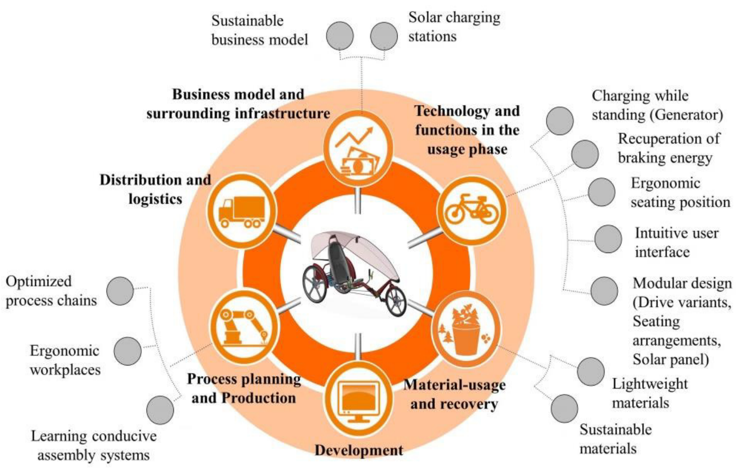

Fig. 2: Targeted Sustainability improvements along the SUW lifecycle

5. Conclusion and practical implications

The primary focus of this work is to provide insights into the challenging task of integrating research approaches from different fields in sustainable manufacturing in one single application example. A case study was presented which described the collaborative effort of eight research projects for improving sustainability of a pedelec.

One insight in this context was that combining different research approaches for sustainable manufacturing doesn't automatically lead to a more sustainable product. Only if all stakeholders coordinate their activities, practical barriers of implementing sustainability can be identified. Nevertheless, the process of physical design and manufacturing of the SUW helped to understand how the different activities in the value chain are interrelated and how they influence the sustainability dimensions. Moreover, synergies and further research potential between the involved projects could be revealed.

The discussed outcomes are primarily oriented on academic purposes. Further research is needed in order to evaluate of how the different approaches will work in a corporate context, where sustainability is only one of many requirements for a value creation network. Nevertheless, there are also implications for industrial application.

The utilized lifecycle view has been proved to be beneficial, since it allows a comprehensive consideration of sustainable aspects within value creation networks. However, value creation activities are usually dispersed among stakeholders in various functions, divisions or companies. In order to achieve a way of collaboration which goes beyond detailed requirement lists, harmonized targets or incentive schemes are necessary. If a common definition of sustainability exists regular "lifecycle reviews", consisting of an interdisciplinary team of experts in all lifecycle stages, should be performed. These compliance checks could be an important step towards improving products from an economic, environmental and social perspective.

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