Making Circular Economy Possible with Optimized Product Development

Many hopes currently rest on the success of the circular economy. To gradually make this a reality in a world of complicated material flows, clever design processes are central, as these play a key role in the ecological, economic and social impact of a product. But when exactly should measures to implement circular processes be taken? Realistic solutions for the integration of aspects of the circular economy in the early stages of the design process still receive far too little consideration.

Keywords

lean method, makigami, circular economy, product development, circular product design, EU Directive 2009/125/EC, ecodesign approaches, environmentally friendly product design, eco-friendly product design, product carbon footprint

Annika Pruhs, M.Sc. is a Research Associate at the Institute for Industrial Ecology at the Pforzheim University of Applied Sciences.

Anina Kusch, M.Sc. is a Research Associate at the Institute for Industrial Ecology at the Pforzheim University of Applied Sciences.

Prof. Dr.-Ing. Frank Bertagnolli is Professor of Lean Production and Resource Efficiency at the Pforzheim University of Applied Sciences, researches at the Institute for Industrial Ecology and heads the Bachelor's degree program in Business Administration/Sustainability and Resource Efficiency.

Prof. Dr. Tobias Viere is Professor of Energy and Material Flow Analyzes at the Pforzheim University of Applied Sciences, conducts research at the Institute for Industrial Ecology and heads the Life Cycle & Sustainability Master's degree program.

Prof. Dr.-Ing. Jörg Woidasky is Professor of Sustainable Product Development at the Pforzheim University of Applied Sciences and researches at the Institute for Industrial Ecology and the Institute for Materials and Materials Technologies.

Contact

inec@hs-pforzheim.de

www.hs-pforzheim.de/inec

DOI: 10.30844/I4SE.23.1.64

Makigami in the Product Development Process

Using a Lean Methodology to Integrate Sustainable and Circular Product Design

Annika Pruhs, Anina Kusch, Frank Bertagnolli, Tobias Viere and Jörg Woidasky,
Institute for Industrial Ecology, Pforzheim University of Applied Sciences

In order to implement future improvements in circular product properties such as lifespan extension, continued use or high-quality recycling, industrial product development and design processes must take the entire ecological and economic life cycle of products into account. This article uses a company example to explain how such processes can be documented and analyzed using the Makigami method to support a comprehensive "Design for Circularity" concept. The chosen approach facilitates the identification of the application points of circular design decisions and the implementation of validated circular economy principles.

The approaches presented here were developed as part of the "DfC-Industry" research project funded by the German Federal Ministry of Economic Affairs and Climate Action (BMWK), which aims to develop digital solutions for designing resource-efficient products for the circular economy. An industry-independent operationalization of this design approach is intended to ensure industrial usability in the economic cycle using concrete design rules, resource efficiency analyzes and circularity indicators for the product engineering process (PEP).

When it comes to product development, most companies focus on adapting or further developing existing products. However, they can ultimately only overcome the challenges arising from fundamental changes to previously existing framework conditions by developing innovative, sustainable products. Many companies therefore view a sustainable innovation process as a starting point for future-oriented development [1]. The early stages of development influence more than 80% of a product's environmental, economic and social impact. Designers and engineers therefore have a significant influence on sustainable product development due to the way they define product properties such as mass or durability [2]. Hence, it is advantageous if the product life cycle is optimized in the early design phases [3].

An industrial PEP is examined using the "Makigami" method. The aim is to sensibly integrate the methodology in development processes and thus make it usable for circular business transformation.

Analysis and visualization through Makigami methodology

The Japanese term "Makigami" stands for "paper roll" and is also known as a process map or a swim lane diagram. The tool is used to record current and target states as part of a process improvement with the aim of passing on information completely and without waste across different areas. The method visualizes administrative processes. The "paper roll", which can also be a digital image, is divided into parallel lanes that represent the departments or experts involved. Within these pathways, actions and decisions as well as their connections are represented, similar to a flowchart [4]. The analysis of the processes and the creation of the Makigami are carried out in a joint workshop conducted with those involved in the process. The individual processes are discussed and visualized. The final result is a completed and coordinated process document that includes not only a proper process description, but also the identification and allocation of Ecodesign Approaches (EDAs).

Application of the Makigami methodology to a practical example

The industrial partner's product development process is based on a stage-gate process (See **Fig. 1**) [5]. After brainstorming has been completed, the product

The ORCID identification numbers(s) for the author(s) of this article can be found under https://doi.org/10.30844/I4SE.23.1.64

DOI: 10.30844/I4SE.23.1.64

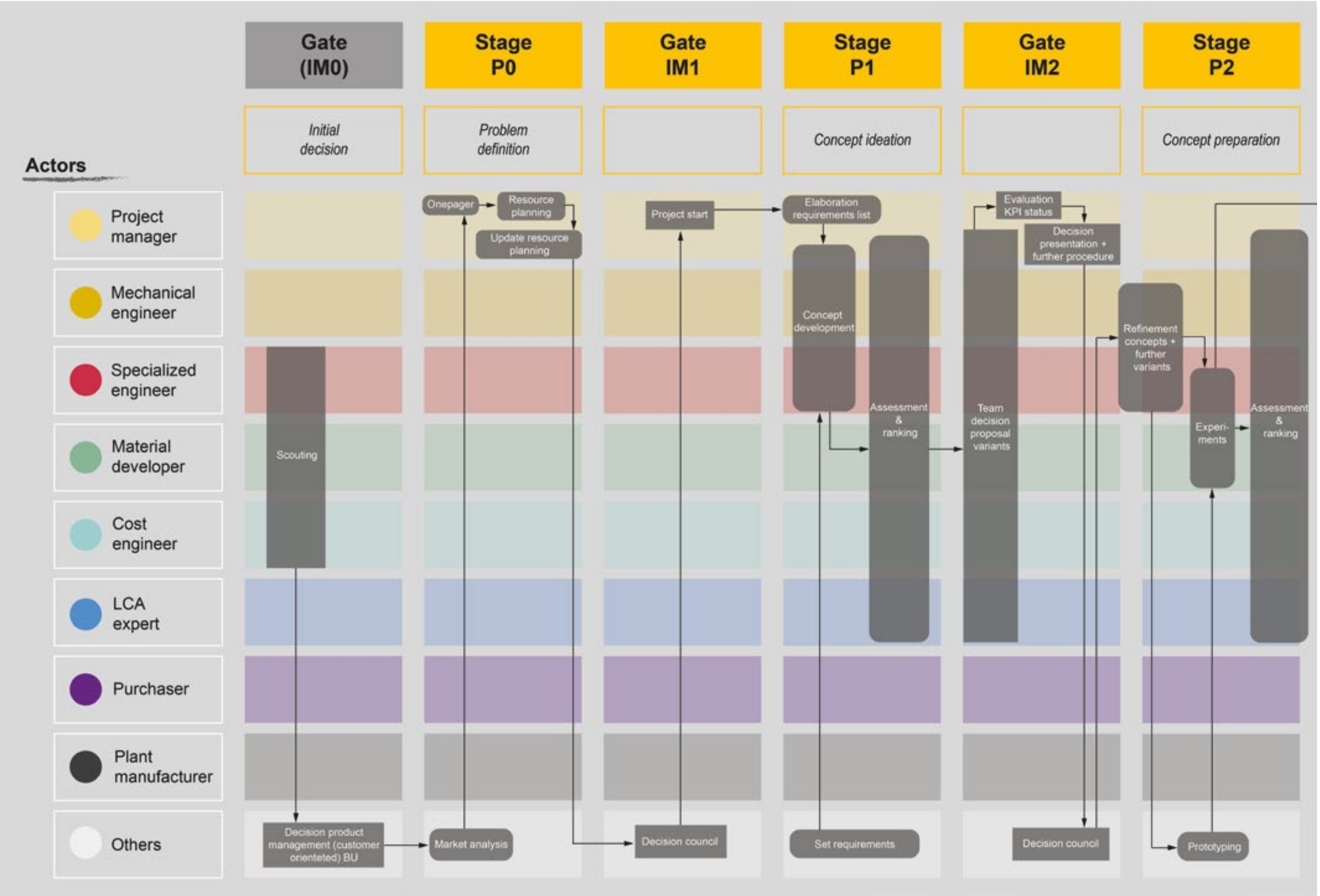

Figure 1: *Activities and decisions at actor level.*

development process is divided into five work steps (stages/phases = P). Companies carry out several measures at the same time within one work step. Between the individual work steps there are milestones or gates (Innovation Maturity Gates = IM, Quality Gates = QG). At these gates, management decides based on the interim results and predefined criteria whether the team should continue on with the project, whether it needs to repeat the last work step again or whether the project will be ended [1]. In addition to the current measures, circular product requirements based on EDAs can be implemented within the stages, which must be checked in the gates.

An interactive workshop will be used to establish a generic PEP. The aim of the workshop is to define the anchoring of circular approaches in the PEP together with all relevant actors [6]. For this purpose, two phases have to be passed: In the first step, a full process capture leads to the description of the actual status quo, which then serves to develop a future circularity-oriented process. The results include both the definition of concrete EDAs and the optimal point in time for implementation of circular solutions.

Current state: Recording the PEP

In the first step, all PEP processes are recorded on a Makigami together with the actors. Key questions support the definition of the relevant activities and working documents.

Actors are understood to be the central stakeholders of the PEP who assume essential functions in the overall process. These include project managers (as decision-making positions with external communication), development engineers (for technical/constructive product design), technical experts, material developers, cost engineers (to run cost assessment of design variants), LCA experts (to conduct ecological assessment), buyers (for selection of suppliers), manufacturing planners (to select manufacturing/production process) as well as other external stakeholders, such as customers and other decision-makers (to provide specifications/requirements for product implementation).

When recording the process, a distinction is made between actions and decisions. These are separated from each other by using different geometrical elements

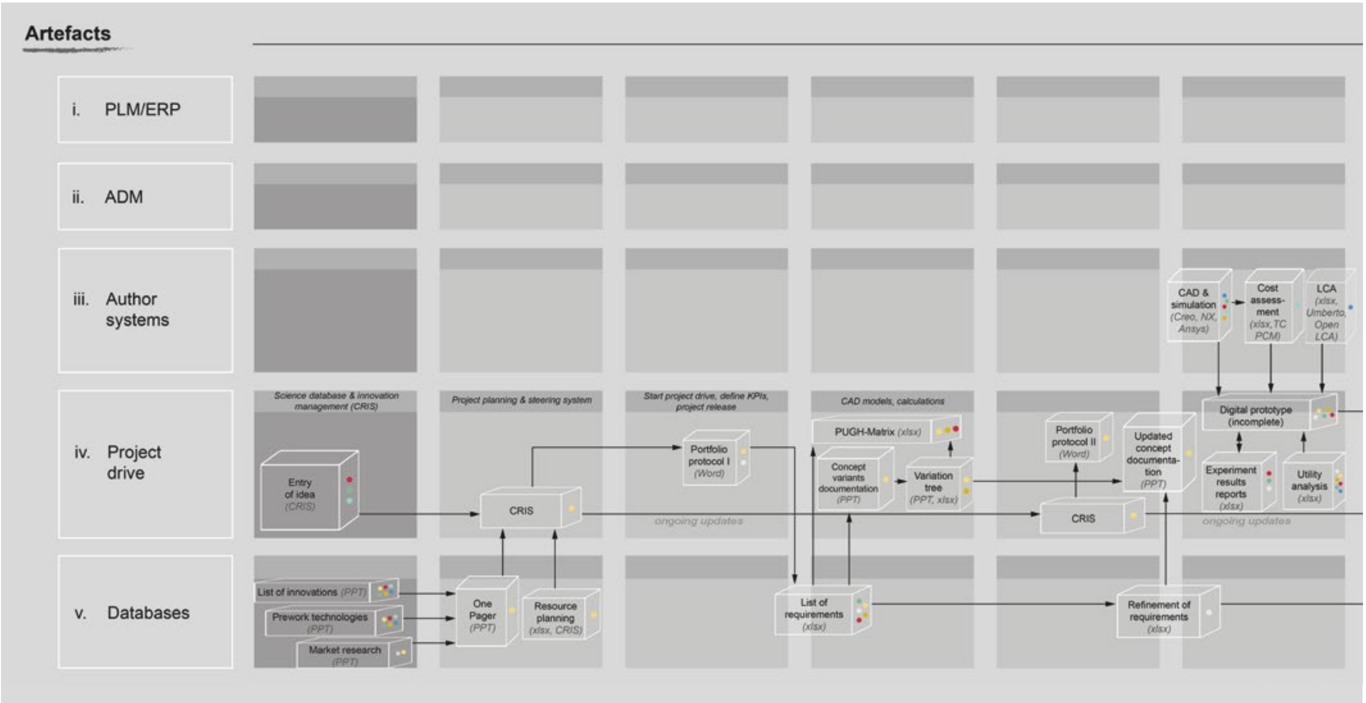

Figure 2: *Software and systems at artifact level.*

in the Makigami (actions are rounded, while decisions are angular; see **Fig. 1**). In addition, color marking is used to assign actions and decisions to the actors involved. The overall process researched here consists of 27 activities and 27 decisions, which are characterized by team decisions and iterative processes to optimize product variants.

The Makigami is supplemented by a parallel artifact collection that records, classifies and hierarchically structures all documents and formalized results of work processes to enable an overview of all the relevant information and interfaces in the PEP. These include, among other things, requirement lists, meeting minutes, hand drawings, CAD models, protocols, calculations and other elements of formalized information storage. The following categories are used for artifact collection and classification: Product Lifecycle Management/ Enterprise Resource Planning (PLM/ERP), Application Data Management (ADM), authoring systems, project drive and data sources such as material databases.

In the present application example, the Makigami method was expanded to include a haptic element: the individual artifacts were made physically available in the form of nestable cardboard boxes, meaning that as the process capture progressed, all work results that were created as a result were available as physical objects in the workshop. The nestability made it possible to map hierarchical relationships between the artifacts. In addition, the involvement of various function-holders in the creation or modification of the artifacts was noted using colored adhesive dots. This supports both process understanding and optimization of the interface structures.

To illustrate this, **Figure 2** shows an excerpt of the artifact collection. The PEP in this case includes 30 artifacts spanning all five categories. The visualization illustrates the complexity and variety of different documents and data formats [7] as well as the potential for interface optimization.

Target state: Timely integration of the EDA into the PEP

The implementation of ecodesign principles in the PEP influences the way products are designed and can therefore contribute significantly to the success of the circular economy [8]. At the operational level, ecodesign leads to product improvement in an environmental sense, which is based on EDAs as a guide [9]. The parameter to be integrated is the degree of circularity of a product or a product feature. The definition of the ecodesign principles was taken from the EU Directive 2009/125/EC [10]. The assignment and description of the EDAs was carried out using the company-specific stage-gate process in collaboration with company experts. It is important for product developers to know the constructive measures to

DOI: 10.30844/I4SE.23.1.64

Process	Actor level	Artifact level
P1 (Concept idea)	**Determination of requirements list:** Selection of all suitable EDAs in requirements list as the starting point for the development process **Concept development:** Consideration of EDAs in development process **Evaluation and classification:** Qualitative inspection of EDAs	**Requirements list:** Definition of all selected EDAs to take into account during product development **PUGH Matrix:** Comparison with alternative concepts
P2-IM4 (Concept preparation up to concept decision)	**Evaluation and classification:** Iterative environmental assessment of all functional prototypes	**LCA Tool**
IM4/QG0 (End of concept preparation)	**Proof of concept:** Quantitative inspection of EDAs	**DfE Checklist:** Inspection of prioritized EDAs from PUGH matrix and integration of these in the requirement management tool
IM4/QG1 (Concept development)	**Design Freeze:** Effects on product properties and draft goals (iterative deviations excluded) EDAs can still be changed up to the point when the final supplier is determined (i.e. to deliver materials or components with a certain carbon footprint); the environmental impact of internal manufacturing processes can still be changed until all details and parameters are set for the start of manufacturing.	**PCF:** Creation of Product Carbon Footprint for virtual and physical prototypes, with iterations across different templates
IM4/QG2 (Product/process development)	**Supplier selection:** The choice of suppliers affects the environmental impact of external manufacturing processes; indirect impact on the presence of hazardous materials, environmental impacts and recycled materials	
IM4/QG4 (Start of manufacturing)	**Start of production and market entry:** EDA environmental impacts: Purely product-specific parameters can be adjusted between QG2 and QG4 (e.g. waste output, layer thickness when coating, machine energy consumption, etc.)	

Figure 3: *Essential features in the product development process.*

implement towards a circular product, but also to know the ideal time for this implementation. A combination of informal and timely recommendations for action is therefore crucial for sustainable product development.

The EDA for "environmental impact" is continuously taken into account, starting from the first functional prototypes (P3) using an ecological assessment (LCA). In addition, the EDA for "substances of concern" must be observed due to legal regulations (e.g. RoHS/REACH). All other EDAs can be selected and added to the requirements list for a specific product from the idea generation phase onwards. After successful implementation of the EDAs, series development of the circular product begins after the incubation phase.

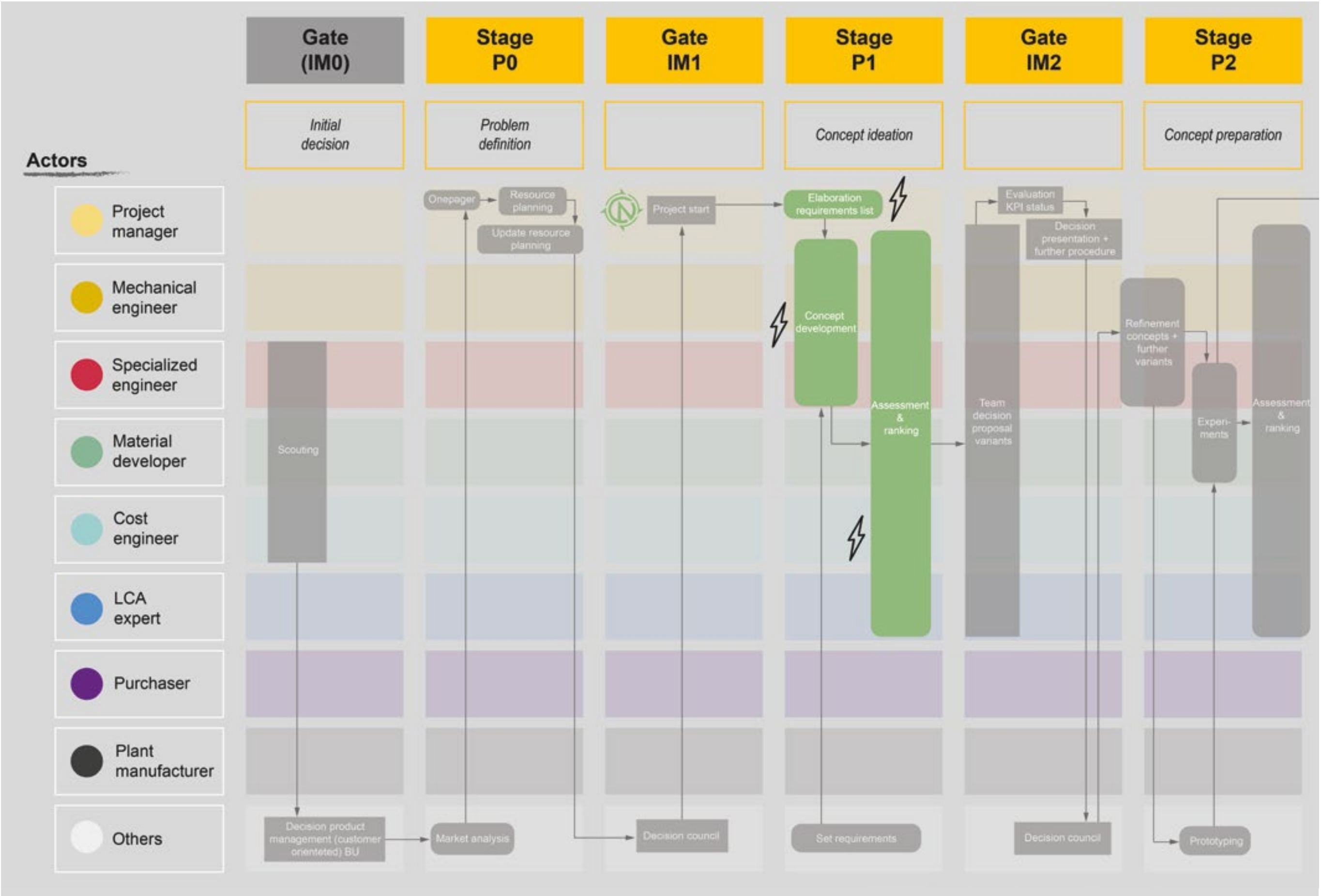

Figure 4: *Integration of Ecodesign approaches at actor level.*

In **Figure 4**, the current product development process is linked to recommendations for action from the respective EDA. This allows the user to assign specific circular measures to the respective phases of the process. The current process will be developed into a “future” scenario.

Discussion of the method and results

The content and timing of the ecodesign recommendations for action presented here may provide a general idea for circularity implementation, although deviations from the PEP will occur depending on the company. The solutions shown here are examples and should therefore be supplemented or adjusted to fit unique company requirements. The “Makigami” method enables such adjustments as well as further detailing and the selection of the EDA that is appropriate for the respective development project. Thanks to its compact form of representation, the Makigami is suitable as an orientation aid, especially at the beginning of product development. The implementation of selected EDAs also leads to challenges in indicative measurability due to the different complexity of the EDAs or in difficulty of data collection. The actual implementation in the target process must be carried out in accordance with standards and with additional verification through individual control instruments within the gates. This study has attempted to visualize this process as generically as possible. However, this is not fully free from industry-specific terms, such as the software used, and therefore cannot be completely generalized. However, the representation of the entire process enables a holistic view of the PEP and the interfaces at the artifact level.

One challenge lies in linking existing data and software types with the EDAs. Future automation offers the potential to reduce these complex structures and simplify their consideration and evaluation within the design environment [11]. When developing sustainable products, those involved in the design process can benefit from multi-criteria quantitative sustainability information [12], which is available in the early phases of product development.

Conclusion and implementation

Product design plays a crucial role in the ecological, economic and social impact of a product [2]. Process visualization using Makigami enables a holistic overview of the PEP in order to recommend ideal points in time for integrating circular measures. The transferability to different PEPs is very high. The target process makes it clear that the greatest potential can be addressed right at the start of development, in the innovation process. If all relevant EDAs are integrated into the process as a requirement at this point, they can be implemented in the product in following phases and then be checked iteratively ("design instead of re-design"). This is because from the "design freeze" onwards, if any changes are necessary, these will require a great deal of time and money to implement. A systematic recording of the artifacts created in the PEP identifies interfaces for the future automation of optimization and review measures: By embedding circular decision-making aids in the company's IT landscape and coupling them with other models, such as ontologies, the development of circular products can be simplified. The generic Makigami forms the starting point for a transparent process consideration with the aim of circular improvements. However, company-specific adjustments are necessary for long-term integration in practice. The model presented can be adapted to individual processes or developed in a workshop as described. This type of joint recording with all actors enables a holistic understanding of the EDAs and thus integrative process optimization.

This article was created as part of the "DfC-Industry" project, which is funded by the Federal Ministry for Economic Affairs and Climate Protection and the Jülich project management agency under the funding code FKZ 03EI5005A. The authors thank Dr. Torsten Hummen and Dr. Ralf Mendgen from Robert Bosch GmbH for the fruitful cooperation and especially for the support in the recording and development of the Makigami.

Bibliography

[1] Scholz, U.; Pastoors, S.; Becker, J. H.; Hofmann, D.; van Dun, R.: Praxishandbuch Nachhaltige Produktentwicklung. Berlin Heidelberg 2018.

[2] Molzbichler, K.: Nachhaltiges Design und User Experience – Digitale Transformation und die Auswirkungen der Gestaltung auf Mensch und Umwelt. In: oekom, Hochschulschriften zur Nachhaltigkeit 2019, p. 82.

[3] Buchert, T.; Neugebauer, S.; Schenker, S.; Lindow, K.; Stark, R.: Multi-criteria Decision Making as a Tool for Sustainable Product Development – Benefits and Obstacles. In: Procedia CIRP 26 (2015), pp. 70-75.

[4] Bertagnolli, F.: Lean Management – Introduction and In-Depth Study of Japanese Management Philosophy, 2nd Edition. Berlin 2022, pp. 224-225.

[5] Engeln, W.: Methoden der Produktentwicklung. München 2006, p. 18.

[6] Widmann, U.; Weissinger, J.; Breitling, T.; Hackenberg, U.; Wundram, K.; Goß, S.: Produktentstehungsprozess. In: Pischinger, S.; Seiffert, U. (ed): Vieweg Handbuch Kraftfahrzeugtechnik, 9th Edition. Wiesbaden 2021.

[7] Lashin, G.; Stark, R.: Virtuelle Produktentwicklung. In: Bender, B.; Gericke, K. (Hrsg): Pahl/Beitz Konstruktionslehre – Methoden und Anwendung erfolgreicher Produktentwicklung, 9th Edition. Berlin Heidelberg 2021.

[8] Kamp Albæk, J.; Shahbazi, S.; McAloone, T. C.; Pigosso, D. C. A.: Circularity Evaluation of Alternative Concepts During Early Product Design and Development. In: Sustainability 12 (2020) 22, p. 9353.

[9] van Doorsselaer, K.: The role of ecodesign in the circular economy. In: Circular Economy and Sustainability (2022), pp. 189-205.

[10] Europäische Kommission: Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC. 2022.

[11] Babiceanu, R. F.; Seker, R.: Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook. In: Computers in Industry 2016 (81), pp. 128-137.

[12] World Economic Forum, Ellen MacArthur Foundation: Intelligent assets – Unlocking the circular economy potential (2016).