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A Study-based Assessment Of Challenges Towards Production-oriented Product Design Within Fuel Cell Technology

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Abstract

Fuel cells are a viable option for clean transportation, particularly for heavy-duty vehicles. As a result of this trend, significant scaling of production volumes is emerging in recent industrial announcements, which also correlates with an increasing degree of automation. However, the latter requires an adaptation of the product design of the fuel cell, which is currently designed for manual production processes and therefore for small production volumes. Furthermore, product design is strongly determined by performance and cost requirements, so production-related requirements tend to receive less attention. The described situation leads to a conflict: on the one hand, the requirements of mass production are unclear, but on the other hand, these requirements are necessary to design the product specifically for mass production. This paper aims to examine the described conflict focusing on the entire product life cycle of the fuel cell from product development to the production ramp-up. Therefore, an expert survey with 65 participants from the industry was performed and the key results are presented. Based on these results, central requirements are derived for a methodological framework to address the above-mentioned challenges. The overall aim of the proposed framework is to integrate manufacturing requirements into product development at an early stage to realize an increasing overlap between product and process development. Finally, a literature review focussing on product and process development is conducted and the identified methodologies are evaluated against the defined requirements. Based upon the identified gaps in scientific theory, a four-stage methodological framework is proposed to address the described conflict at the requirements level.

Keywords

Fuel Cell; Production Engineering; Production Requirements; Product Design; Design for Production

1. Introduction

While electrification through traction batteries is gaining ground in the passenger car segment and will remain an established technology in the future, heavy-duty applications in particular represent a market for fuel cells. [1] The potential of fuel cells can be seen in the current industrial announcements. It can be observed that 25 million individual fuel cells were produced in 2018 and 103 million in 2022. By 2030, a production of 265 million cells is forecast as the lower limit, which correlates with an increase of at least 157%. [2] Accordingly, it can be stated that the market is responding to the potential of the fuel cell and a high production scale is expected. However, a reduction in the cost of fuel cell electric vehicles is necessary to enable the market penetration of the fuel cell. [3] The cell components membrane electrode assembly (MEA) and bipolar plate (BPP) can make a significant contribution to reducing system costs. In today's fuel cell systems, these are responsible for 45% of the costs for a production capacity of 1,000 systems per year. [4] The cost reduction of cell components is mainly made possible by scaling production, which has a significant impact on costs, especially up to 100,000 stacks or systems per year. [5] However, today's production capacities are in an area where there are very few economies of scale and where primarily manual

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processes are used. [2,6] For this reason, the product design is expected to be insufficiently designed for scaled production. However, in the anticipated scaling of fuel cell production, an increasingly production-oriented product architecture is motivated. For this reason, an industry study is carried out to identify the current challenges of production-oriented product development.

2. Methodology

In preparation for the main study, an industry benchmark was conducted over three months. Nine selected entities participated in the industry benchmark, including seven machine and plant manufacturers, one fuel cell manufacturer, and one research institute. The aim was to identify the main challenges in the fuel cell industry at the interface of product and process development. Therefore, four thematic blocks were formulated (product development, process development, modularization, parallelization of planning processes), which were discussed using a guide. Based on the results of the industry benchmark, three fuel-cell-industry-related challenges were derived:

(1) Compared to other industries, product and process development in the fuel cell industry is characterized by many iteration loops, which lead to high costs in the development phase
(2) In particular, start-ups in the field of fuel cell development have significant know-how within the product, but they often lack expertise in large-scale production
(3) The lack of expertise in large-scale production makes it difficult to assess the fulfilment of the production-related requirements of the product designs

Based on the findings from the industry benchmark, five working hypotheses were derived for the main study (Table 1). The hypotheses can be assigned to the WANGENHEIM phase scheme in the phases from product development to pre-series production [7]. Pre-series production is crucial, as it is directly connected to the product development phase and is used for early problem detection [9,8]. For each hypothesis, several questions were formulated in which the participants had to agree or disagree with a statement, estimate values, or assign content. In addition, general questions and questions for experts were formulated. The expert questions were marked accordingly in the questionnaire. The study focused on the components Subgasket, Catalyst Coated Membrane (CCM), MEA, BPP, and the Stack. In addition, the term producibility was introduced and defined as a measure of the extent to which a component is suitable for large-scale production processes and to what extent it fulfills large-scale production-related requirements.

Table 1: Working hypotheses of the industry study

	Subject	Amount of questions
1.	State-of-the-art in fuel cell product development	5
2.	State-of-the-art and changes in fuel cell product design	5
3.	Challenges in fuel cell product design change	5
4.	Pre-series production in fuel cell technology	5
5.	Production-oriented product adaptions	4

The study was conducted in October 2023 and was accessed 96 times after it was sent out. Of these 96 accesses, 65 returns were declared admissible. When the study was sent out, it was ensured that all participants had a connection to fuel cells or production technology. The top 3 participants are people from the fields of research and development (34%), mechanical and plant engineering (22%), and component manufacturers (14%). The other participants are from companies in the field of stack and system production, management consultancy, development service providers, and others.

3. Results

3.1 Industry study

The first part of the study focuses on the state of the art in product development. The participants' median assessment of the technological readiness level (TRL) is seven, which is equal to a technology that is in use as a prototype application in a specific environment [10]. Compared to the TRL, the median of the manufacturing readiness level (MRL) is five and thus corresponds to a phase in which the production processes of fuel cells is in an iterative development stage in which significant engineering and design changes are still being made (see Figure 1 a)). Although the development of the key manufacturing processes takes place in this phase, undefined interfaces between the processes in particular represent a further characteristic and therefore a further challenge of this phase. [11] Due to the continuing development of production technology, the combination of TRL and MRL suggests that the producibility is only insufficiently considered in fuel cell product development. However, it becomes clear that the consideration of production-related requirements in product development must become a much higher priority compared to the status quo (see Figure 1 b)). At present, product development is primarily characterized by costs, functionality, and the fulfilment of lifetime and performance targets (see Figure 1 c)).

It was found that 97% of the participants assume that the product design of the fuel cell will change in the future – 95% of them also agreed with the statement that these changes will be implemented in order to improve producibility. In addition to increased functional integration, the participants also listed a simplified, automation-oriented product architecture, increased tolerances, reduced material thicknesses, the revision of product requirements, and the use of alternative materials as possible product changes. According to the participants, the current product design meets the requirements of small series production (> 1,000 - 10,000 stacks per year and production line, median). However, production output is expected to increase to > 50,000 - 100,000 (median) stacks per year and production line until 2033. Thus, Figure 1 d) also shows that the product design needs to be adapted in order to meet the requirements of future, more automated production capacities.

To successfully design a product according to the required specifications, knowledge of large-scale production is crucial. However, only 42% of the surveyed participants were aware of the relevant processes and innovations in large-scale production of fuel cells. Furthermore, expected innovations were estimated across the entire value chain of fuel cell production. This conclusion aligns with the MRL-observations made in Figure 1 a), showing that process development is characterized by an iterative nature and unclear requirements. The latter was also confirmed by the participants, as only 11% agreed with the statement that they were aware of the product design requirements of large-scale production. Thus, producibility is considered insufficiently in the product development of fuel cells as of now (81% agreement, see also Figure 1 b)).

The relevance of producibility in product design is further emphasized in Figure 1 e). It shows the rejection rate estimated by the participants in the pre-series production of fuel cells. There is a difference in the estimated rejection rates between the components Subgasket (median: 13%), BPP (median: 10%), and Stack (median: 8.5%) as well as CCM (median: 15%), and MEA (median: 24%). Even if the median of the CCM is in a similar range to that of the Subgasket, a deviation towards higher rejection rates (75% quantile and upper whisker) can be recognized. A comparable trend is observed in the BPP and the stack. This is due to left-skewed data, i.e. the data collected does not correspond to a normal distribution where the median is below the average [12]. Furthermore, the interquartile range is particularly small when analyzing the Subgasket, which indicates a low scatter width of the collected data. The interquartile range is defined as the length between the 25% and 75% quantile [12]. The interquartile range of BPP and Stack is larger compared to that of the Subgasket, while that of CCM and MEA is the largest. The comparison with the assessment of the producibility of these components shows that higher rejection rates of CCM and MEA correlate with a lower estimated producibility (Figure 1 f)). The producibility was estimated qualitatively by the participants.

Accordingly, the producibility of Subgasket, BPP and Stack were estimated to be the highest. However, there is a significantly wider range of values compared to the rejection rate – shown by size of the whiskers. By comparison, the interquartile range and the rejection rate have a similar size. However, this value is noticeably low for the MEA.

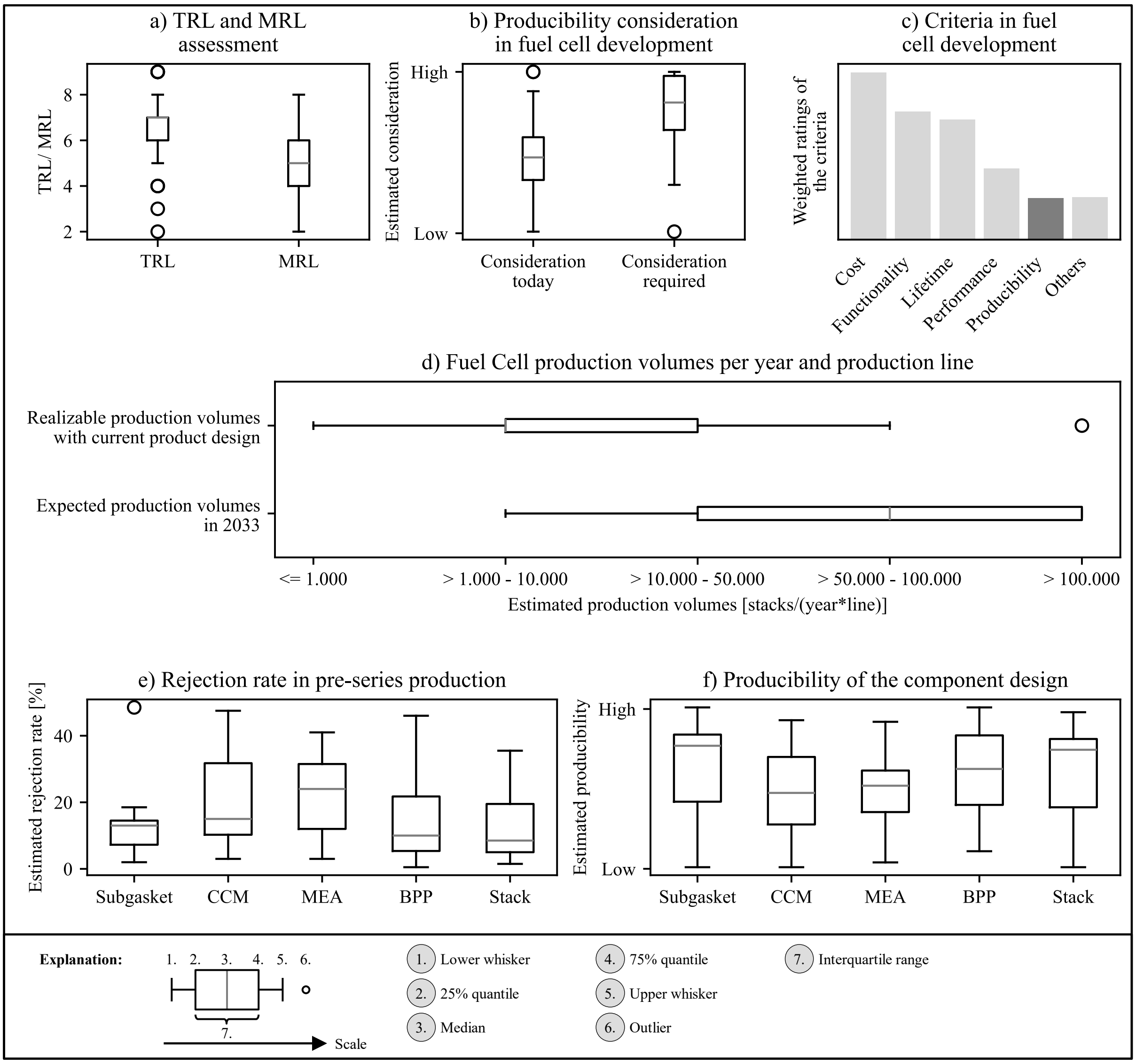

Figure 1 - Summary of the major industry study results: a) TRL and MRL assessment, b) Consideration of the producibility in fuel cell development, c) Key figures in fuel cell development, d) Assessment of the implications of the product design on the production volume, e) Component-specific rejection rate in the pre-series of fuel cell production, f) Component-specific producibility of fuel cell components

The dilemma caused by the inadequate consideration of producibility in product development and the resulting high rejection rate in pre-series production was investigated further as part of the study. Here, 95% of the participants agreed that an adaptation of product specifications in pre-series production to improve producibility is beneficial. Nevertheless, there is also the challenge of not affecting other key figures or product specifications negatively (76% agreement). One solution could be an increasing integration of product and process development, in which potential product adaptations are considered during initial product development. However, 84% of participants agree with the statement that this is not or only insufficiently implemented in current planning processes. Furthermore, the participants stated that there is a lack of appropriate tools for industrial practice (74% agree).

3.2 Derived industry challenges

Based on the detailed results of the industry study, the challenges identified within the industry benchmark can be further detailed and completed:

(1) Lack of production requirements: Due to the development of new production processes, the requirements of series production in terms of product design are unclear. Specific technical production requirements are not yet fully defined due to the low MRL.
(2) Production-oriented product design: The key figure producibility is currently deprioritized compared to other key figures. It is becoming clear that it will serve as a key enabler for the expected large-scale production. In combination with the first challenge, a conflict at requirements level is emerging.
(3) Delay in product specification: Individual components do not or only insufficiently fulfil technical production requirements. This leads to highly iterative product specification between product and process development and results in unforeseen delays in series development and the start of production (SOP).
(4) Product flexibility: The conflict at requirements level makes a flexible product necessary. This should be adaptable to ensure producibility in all phases. Appropriate tools for industrial practice do not exist or are inadequate.

4. Literature review and methodological framework

4.1 Derivation of content-related requirements

The challenges faced by the industry (section 3.2) are used to derive requirements for a methodology that can be applied in the described area (see Figure 2).

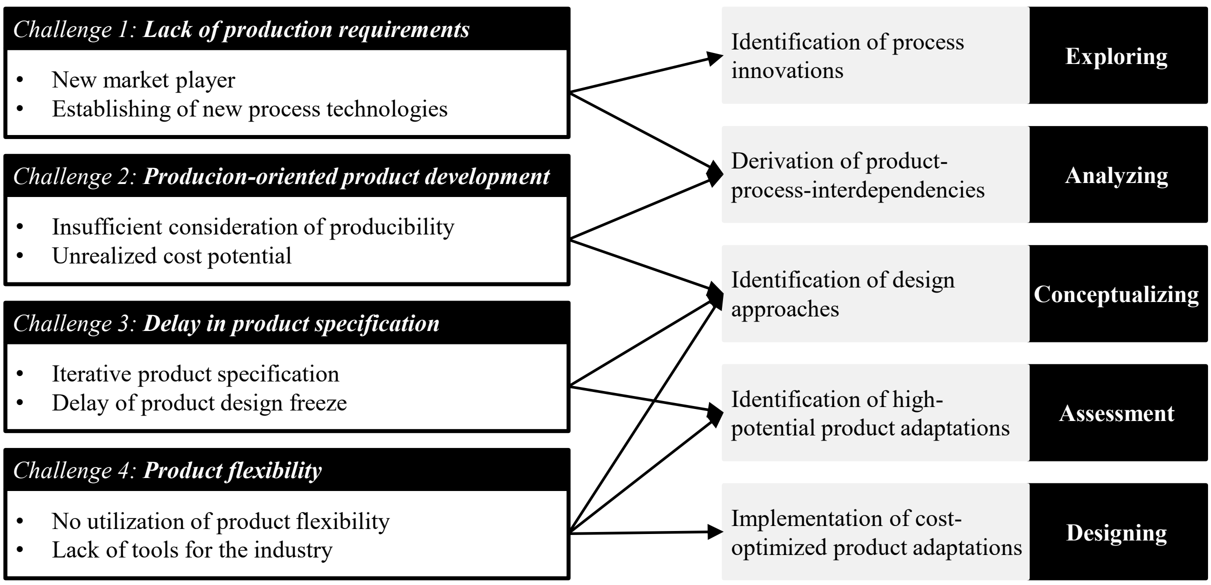

Figure 2: Derivation of content-related requirements for a methodological framework from the identified industry challenges

Two primary requirements can be derived from the uncertainty regarding the unknown requirements of production technology. On the one hand, there is the requirement that process innovations in the field of fuel cell production must be identified at an early stage (exploring) and that these must also be linked to product characteristics (analyzing).

The need to design products increasingly production-oriented results in the third requirement (conceptualizing). This means that design approaches must be presented that consider all requirements of a product holistically. Additionally, flexible design guidelines need to be defined that can be utilized during product development and pre-series production.

Due to the delays in product development and the SOP, it is necessary to be able to identify high-potential product adaptations (assessment). For instance, scrap in pre-series production can be used as a key figure, which can be reduced by optimizing the product design. Since not every design approach can be implemented cost-effectively, the most economical solutions must be realized. This demand results in the fifth requirement (designing).

In addition to the content-related requirements, there are formal requirements that can be derived from STACHOWIAK's model definition and that ensure a structured approach to model development. [13] The formal requirements of empirical and formal correctness, productivity, manageability, and low effort can be derived from this. [14] These must also be fulfilled by the methodological approach.

4.2 Identification of the theory deficit

The requirements for a methodological approach derived in 4.1 can be used to assess the extent to which scientific approaches have already been developed for the described industrial challenges. Accordingly, the requirements serve as an evaluation criterion for existing scientific approaches. For this purpose, relevant approaches were first identified and further narrowed down as part of a literature search. The theoretical approaches can be categorized thematically in the fields of product development and requirements engineering, process design, and production ramp-up (Figure 3).

		Exploring	Analyzing	Concept-ualizing	Assessment	Designing
Product development, requirements engineering	LUCAS METHODE [1989]	○	◕	◑	◕	◕
	BOOTHROYD & DEWURST [1994]	○	◕	●	◕	◑
	BAUER [2008]	○	◔	◔	●	◕
	RUDOLF [2013]	○	●	◔	◑	◔
	BREUNIG [2017]	○	◔	○	◑	◔
	SAROVIC [2018]	○	◑	◔	○	◕
	DIEKMANN [2021]	○	◔	○	○	◔
	TROMMNAU [2021]	○	◕	●	◕	◑
	MOHSSENI [2021]	○	◔	◑	◕	◕
	HAUNREITER [2021]	○	◔	○	◔	○
Process design	HEIMES [2014]	●	◑	◔	○	○
	SCHÖN [2022]	●	◕	○	◑	○
Production Ramp-Up	LAUFENBERG [1995]	○	◔	○	○	◔
	WANGENHEIM [1998]	◔	◔	◑	○	○
	MAUE [2016]	◑	◑	◔	◑	○
	BASSE [2019]	○	◔	◔	○	◑
	NGO [2021]	◔	○	◔	○	○

Figure 3: Summary of the literature review and assessment of the identified scientific work

In industrial practice, products in the fuel cell industry are predominantly designed and developed according to other key figures than producibility. This leads to delays in the development process and the SOP. The literature contains various benchmarks for the cost and performance key figures, which significantly affect the design of fuel cell products. [15,16] However, it has become apparent that there is no standardized and quantified definition for the key figure producibility that can be used for the development process.

Furthermore, the research approaches in the field of "Design for X" take insufficient account of flexible components, such as those typically used in fuel cells. Although TROMMNAU addresses flexible components, his methodology refers to automotive wiring harnesses. [17] These are also fed into a conventional assembly process, but the cycle times in assembly cannot be equated with those in the large-scale production of fuel cells.

In conclusion, it was shown that product adaptation during production makes sense in fuel cell production. However, the main research approaches that can be assigned to the production ramp-up do not address product adaptations and primarily refer to the adaptation of production technology. Accordingly, the unknown process technology and the lack of experience is not included in these research approaches. Finally, it can be concluded that a methodology that addresses all five content-related requirements and at the same time meets the requirements of the fuel cell industry does not exist.

4.3 Overcoming challenges towards production-oriented product design

The approach is generally based on ULRICH and aims to solve the defined problem using structured models. This enables a solution to be offered to industrial practice. [18] According to PATZAK, different types of models can be described, including descriptive models, explanatory models, predictive models and decision models. [14] In general, these are characterized by constituent features, whereby STACHOWIAK distinguishes between mapping features, shortening features and pragmatic features. [13] Figure 4 outlines the broad concept of the methodology, in which the different models are assigned to the real system or the model world.

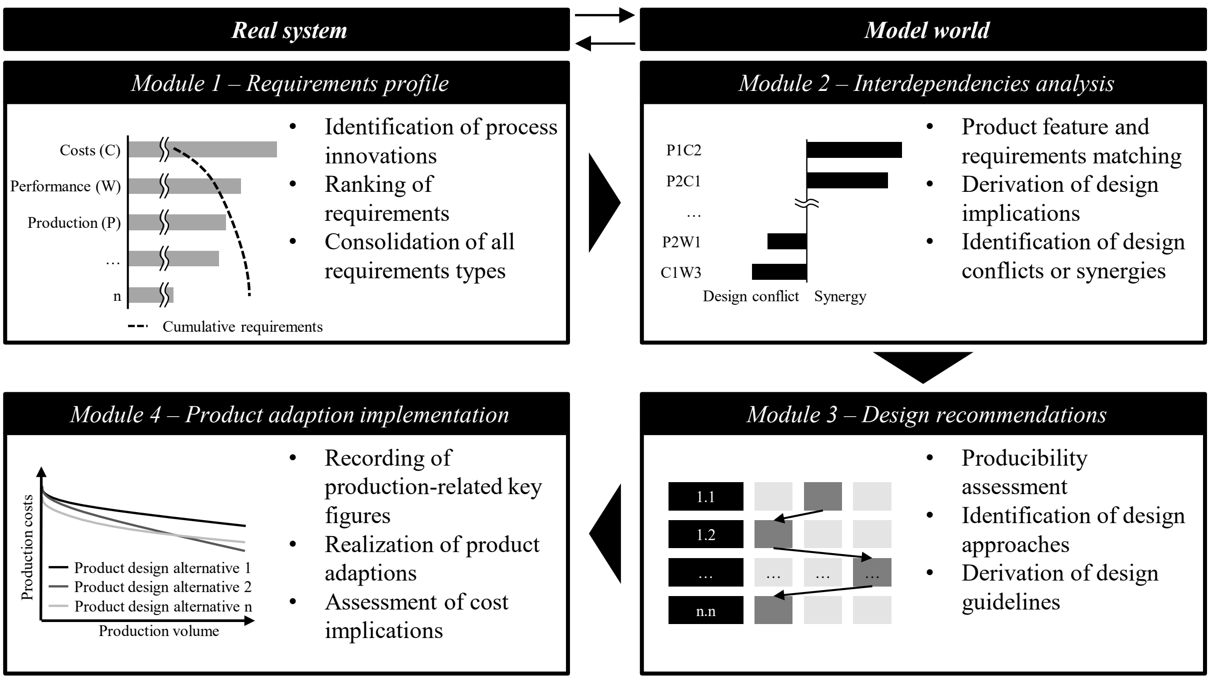

Figure 4: Four stage methodological approach to address the identified industry challenges

The aim of the first module is to derive a holistic product requirements profile. In addition to conventional requirements, this profile takes account of production-related requirements. For this purpose, technology and innovation screenings are carried out, which contribute to the identification of possible process innovations. Finally, by extracting and evaluating product-specific requirements, the requirements that are directly related to the product are derived. These are then combined with other product requirements (see Figure 1 c)) and evaluated in terms of their relevance. As a result, a weighted overview is provided of which requirements a product must fulfil and to what extent.

As soon as the requirements profile has been completed, module two analyzes the extent to which different requirements have conflicting or synergetic implications for the product design. For this purpose, a link between product features and requirements is established to create a consistent product requirements system. This enables the user of the methodology to directly connect requirements of any kind with features of the product and subsequently evaluate them. Qualitative or quantitative scales can be used as evaluation criteria. Finally, combinations of requirements are formed and the implications for specific product features are evaluated.

In the third module, the described implications are combined to derive recommendations for product design based on generic design approaches. The aim is to formulate these in a consistent and production-oriented way. For this purpose, the definition of producibility is derived from the technical production requirements. The basic approach is that fundamental producibility must be given to fulfil the minimum requirements of series production. As a result, there is an assessment scale for quantifying possible product feature characteristics in terms of producibility. In parallel, product-related design approaches are identified, evaluated, and specified, which can be understood as a tool for implementing the specific requirements profile. Finally, the design implications from module two are combined with the aid of the specified design approaches. The introduced evaluation scale for producibility is used to make design recommendations that meet the requirements of the product in a production-oriented way.

In the fourth module, production-related key figures are used until pre-series production to identify necessary product adaptations. In particular, the costs, time, and quality in production and the change costs can be used as a benchmark to assess the extent to which product adaptations are necessary. Furthermore, these figures can be used whether the adaptions can be realized economically. For the identified product adaptations, the results from module three are used to derive recommendations for action for the specific use case. The result is a cost assessment of which design recommendation is the most economical option in terms of meeting production requirements.

In summary, the aim is to use the described methodology from the concept phase through to pre-series production as a consistent tool based on WANGENHEIM and to overcome the

- lack of experience with the unknown production technology
- through a flexible, production-oriented product design,
- which can be adapted with the help of production data up to pre-series production in order to meet production-related key figures. [7]

5. Conclusion

It was shown that the production of fuel cells is scaling due to their potential in heavy-duty applications. In addition to the ongoing expansion and further development of production technology, an increasingly production-oriented product development is also required. To identify the current challenges in the industry, an industry benchmark was initially carried out with nine companies. The results were used to construct a more specific industry study in which a total of 65 people took part. The outcomes were gathered in five categories using 24 questions. It became clear that process development is less mature than product development. Thus, producibility is not given sufficient consideration in product design. Compared to the status quo, the participants expect product design to be further developed in favor of scaled production. Accordingly, the key figure of producibility will be given greater weight in future compared to current key figures. At the same time, the study also revealed that a more production-oriented product design correlates with fewer rejects in production. To support the process of production-oriented product development, the participants show that more integrated product and process development, considering future process innovations, is required. The results of the study were finally summarized in four main challenges. Based on these challenges, requirements for a methodological approach were then derived and available literature was evaluated against these requirements. It was found that no approach from the literature meets the related requirements. As a result, a four-stage model was proposed, which is first captured in the real world and then transferred to the model world. By gathering product requirements holistically, the four modules are intended to derive design recommendations that can be applied up to pre-series production. However, the design recommendations should be formulated considering process innovations and a scale for producibility.

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Biography

Niels Hinrichs (*1996) is a research assistant at the Chair of Production Engineering of E-Mobility Components (PEM) at RWTH Aachen University. He studied mechanical engineering with a focus on energy and process engineering at Ruhr-University Bochum.

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