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Procedia CIRP 116 (2023) 119–124

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference

System Orientation as an Enabler for Sustainable Frugal Engineering: Insights from Automotive Material Development

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Abstract

Research about barriers towards green material transition in automotive often points to technical or regulatory barriers. Contrary we emphasize an under-researched inhibitor, namely the underlying innovation assumptions and technical requirements in organizations that define themselves as quality-driven. As sufficiency represents a vital strategy to encounter corporate sustainability, especially Western organizations are forced to rethink their "bigger and better innovation ideologies". Thus, our research shows that overly high and complex technical requirements that may not be relevant for a specific use case represent a serious barrier for the implementation of often inferior secondary polymer materials.

We address the emerging challenges through the theoretical lens of frugal engineering that offers a promising contribution to corporate sustainability due to its focus on core functionalities and optimized performance levels. Using a mixed-method expert interview study as part of an ongoing action research project within a leading German automotive OEM we develop a system-oriented approach for sustainable and frugal engineered polymer materials. The method will support engineers and product developers to overcome overengineering and mitigate requirement-based inhibitors of life cycle engineering. Future research should examine the discussed barrier in other industries and substantiate the applicability of our proposed method with further case studies.

Keywords: Frugal engineering; frugal innovation; frugality; material development; system engineering; automotive

1. Introduction

Considering the major global responsibility of the automotive industry for achieving the Sustainable Development Goals (SDGs), research is intensively engaged with the topic of green material transition, e.g., the gradual substitution of virgin with secondary materials [1]–[3]. With particular regard to *polymers*, scholars emphasize diverse transition barriers in the automotive sector, such as cultural and regulatory inhibitors [1], high necessary investments and high organizational inertia as well as management reluctance and bureaucracy [2]–[4].

One further aspect that is frequently addressed in this context is the limited product quality that arise in a circular material system, thus limiting possible applications that meet the corresponding requirements for automotive materials [4]–[6]. Even though the requirements for materials in automotive engineering are certainly high, the literature is silent on the question of whether these requirements are *too high*, meaning that qualities are demanded that exceed the requisite performance for the respective use case (commonly referred to as "*overengineering*"). An example is a technical design with insufficiently differentiated material requirements so that polymers with lower properties would also meet the required performance for the intended application. Particularly for polymers which can be subject to strong downcycling in recycling processes [5], overly high requirements are likely to result in an avoidable limitation of market supply and increase in development costs.

We encounter the topic through the theoretical lens of frugality, a research stream that has been discussed in particular in the academic discipline of (global) innovation [7] and sustainability management [8], [9]. Scholars found that products that originate from emerging markets like India follow different innovation paradigms contrary to the prevailing "*bigger and better ideology*" of advanced economies [10], [11].

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10.1016/j.procir.2023.02.021

In that sense, innovations that emphasize affordability, a concentration on core functionalities and an optimized performance level are called Frugal Innovations (FI) [12], [13]. In relation to product development scholars state that Frugal Engineering (FE) does not exclusively stress reduction measures alone, but rather critically evaluates what is required for the corresponding use case in order to engineer innovation outcomes as tailored and cost-optimized as possible [14]. In view of the intensifying environmental challenges, sustainability-oriented engineering research increasingly calls for sufficiency as an enabler for sustainability [15]–[18] making FI a potential global mega-trend [19], [20].

For this reason, the purpose of this paper is twofold. First, the described challenges in the automotive industry are related to the concept of FE analyzing the hypothesis whether too high material requirements represent a systematic barrier to secondary polymers.[1] In addition, we explore the reasons *why* organizations tend to set their material requirements too high.

Second, we propose a method inspired by System Engineering (SE) that applies the central principles of FE at the operational level. Thereby, the focus is not on the identification of customer needs but on the *effective translation* of these needs into more abstract material requirements. Furthermore, we argue that the method allows engineers and product developers to *identify overengineered requirements* that can be reduced for future applications.

2. Theoretical Background

2.1. Sustainable Frugal Innovations and Engineering

In contrast to the common engineering principle of Western companies that "values perfect solutions above general usefulness" [11, p. 27] and is often a result of historically induced path dependencies [21], FI follow a high market and customer orientation within R&D.

For this reason, scholars also conceptualize FI as a *golden mean of innovation* [22] or as *affordable green excellence* [23], since product qualities are neither too high nor too low [24] and environmental constraints are managed in an effective and balanced manner [25]. [26, p. 30] define FI "as new or significantly improved products [...] that seek to minimize the use of material and financial resources in the complete value chain [...] with the objective of significantly reducing the total cost of ownership and/or usage while fulfilling or even exceeding certain pre-defined criteria of acceptable quality standards." As one of its key principles, FE tries to apply conscious reduction in features and performances *without* a resulting downgrade from the customer's point of view [12], [13].

Scholars note that FI do not focus exclusively on environmental improvements of products, but rather integrate environmental, economic and social objectives [8], [27]. Based on our

[1] As [4] and [5] demonstrate, polymer recycling can be carried out in various ways. In this paper, however, we refer to *mechanically* recycled grades typically used in the automotive industry which involves the direct processing and reuse of single-grade polymers from various waste streams.

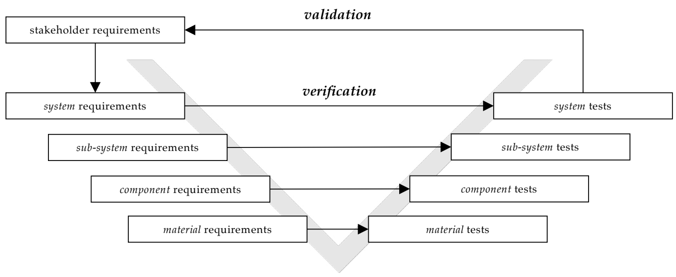

Fig. 1. V-model and system orientation (based on [33], [34])

earlier research, we underscore that principles of FE contribute to what has been discussed as *efficiency* (defined as a reduction of negative ecological impacts), *effectiveness* (defined as a perspective that respects planetary boundaries as the foundation for innovations) and *sufficiency* (defined as a reduction-oriented economic approach, e.g., with regard to conscious consumption or complexity reduction of innovations) [9], [28]. Thus, FI are considered to have a significant contribution to the achievement of SDGs [23], [29] and can therefore represent a vital perspective in sustainable engineering.

Examples of FI in the automotive industry include the Tata Nano, also known as the world's cheapest car, and its competitor, the Renault Kwid, which features higher-end equipment, thereby achieving a great innovation success in the Indian automotive market [30], [31].

Research gaps exist in operationalizing what is meant by *good enough* or an *optimized performance level* and how innovation processes and engineering methods can be specifically designed for FI [19]. In a broader sense, scholars indicate the lack of conceptualization, approaches and empirical research of FE [14]. With our study we aim to address this gap and provide insights how system orientation can be ascribed an enabler role for sustainable FE.

2.2. System Engineering and Material Requirements

In the light of increasing technological complexity, products and development processes become more and more sensitive to errors. The basic idea of SE as presented in the so-called V-model (illustrated in Fig. 1) is to reduce the complexity to a manageable level by breaking down complex systems, such as a car, into subsystems (e.g., interior or powertrain) to a component level (e.g., a switch on the steering wheel) [32], [33]. This differentiation into manageable elements enables the precise definition of increasingly abstract requirements that are tested by respective *verification* measures, such as software or material tests. Further *validation* measures refer to the initial stakeholder requirements or business objectives and confirm whether these are fulfilled by the corresponding system or subsystem [34]. While verification aims to demonstrate that a (sub-)system fulfils all requirements determined in the first place ("building the product right"), validation procedures refer back to the initial stakeholder requirements asking whether the intended objective is fulfilled ("building the right product") [33], [34].

In addition to verification and validation measures (V&V), SE also focuses on the *effectiveness* of requirements that are specified for a system as part of a requirement management process [33]. As shown in Fig. 1, the first step involves the translation of *stakeholder requirements* into *system requirements*, before these are broken down further to more detailed *sub-systems* and eventually *component* and *material requirements*. Therefore, the detailed component or material requirements are interconnected with the broader (sub-)system requirements.

With regard to our study, material requirements refer to the necessary polymer properties that raw material suppliers must satisfy and that are ultimately verified by the OEM in material and component tests, see also Fig. 1. Examples include tensile strength, heat aging resistance or emission requirements.

3. Methodology and Research Design

The data collection was conducted as part of an ongoing action research project in the material development department of a leading German automotive OEM that increasingly experiences the rejection of secondary polymers as a consequence of its material requirements.

Action research is a collaborative research approach in which the researcher solves practical problems (such as the one described above) together with the organization and initiates, manages and scientifically analyzes change interventions based on theoretical findings and models [35], [36]. Within an action research project, the methodology follows a pragmatic research philosophy and therefore makes use of a variety of possible data collection methods, such as interviews, surveys, observations and workshops [35], [37]. For this purpose, [35] proposes an iterative approach using the steps of construction (of organizational challenges), planning, action (intervention) and evaluation.

As part of the initial construction phase, a mixed-method expert interview approach was chosen to answer the question of whether material requirements are a systematic barrier to innovative and secondary polymer materials (n=71, average interview time 31 minutes). The experts are employees from various departments, such as materials development, design engineering and research with at least three years of professional experience in the field of secondary (polymer) materials, and thus observe the barriers as part of their daily work.

First, the participants rated implementation barriers of secondary polymers on a seven-item Likert scale, ranging from “strongly disagree” (1) to “strongly agree” (7) as also shown in Table 1. Due to the fine-grained differentiation of response choices, Likert scales are typically used in surveys and questionnaires [38] and were also previously applied in sustainability research in the automotive industry [3], [4].

Subsequently, a semi-structured interview guide (see Appendix A) was used to address the challenges of requirement management and to understand the causes of overly high requirements from a technological as well as organizational perspective. To satisfy the explorative nature of the research and to avoid potential bias due to prior knowledge of the researchers, the interview consisted of three open-ended sets of questions. By analyzing the interview transcripts with a typical coding procedure as proposed by [39] the causes have been classified into main categories, that emerged as a result of continuous abstraction and conceptualizations of the authors, see also subsection 4.2. Based on the results, a method inspired by the presented V-model of SE was developed in numerous subsequent workshops, discussions and agile development teams, which eventually facilitates more frugal-inspired engineering of secondary polymers as well as the optimization of existing technical requirements.

4. Findings and Discussion

4.1. The Influence of Material Requirements

Table 1 presents the ratings of in total 16 typical implementation barriers of secondary polymers. Based on a mean value comparison, the primary barriers are a lack of knowledge and experience with sustainable materials (1st), the internal bureaucracy and complexity of the development (2nd), an insufficient management support (3rd) and the general market conditions, including volatile pricing or availability of secondary polymers (4th). In fifth place, however, requirement management has already been perceived as a general barrier, primarily because the material requirements are too high, unrealistic or too complex, as indicated by barriers no. 8, no. 9, and no. 10 (each of the barriers mentioned received considerably more approval than disapproval).

Table 1. Results of quantitative part of the study

Barrier	Mean
(1) Insufficient technological performance	4.65
(2) Development costs (too high)	4.38
(3) Component costs (too high)	3.63
(4) General market conditions	5.11 (4th)
(5) Insufficient supply chain cooperation	3.82
(6) Lack of institutional requirements	4.25
(7) Material requirements (general barrier)	5.10 (5th)
(8) Material requirements (too high)	4.97
(9) Material requirements (unrealistic)	4.42
(10) Material requirements (too complex)	4.70
(11) Incentive (low contribution to optimization)	2.30
(12) Entrepreneurial risks (too high)	2.66
(13) Creation of workloads (too high)	3.59
(14) Bureaucracy and complexity of development	5.44 (2nd)
(15) Insufficient management support	5.14 (3rd)
(16) Lack of knowledge and experience	5.49 (1st)

1: strongly disagree; (...); **4:** neutral; (...); **7:** strongly agree

An accompanying correlation analysis of the individual barriers shows that experts who see requirement management as a general barrier (no. 7) also consider the material requirements to be too high (no. 8), unrealistic (no. 9) and too complex (no. 10). The high level of statistical significance of the correlation coefficients (significance level of α=1%) indicates that the relations between the aforementioned barriers are not based on coincidence. Arguably, these findings justify the relevance of this so far rarely discussed barrier and emphasize the need of material requirement reduction in order to foster secondary and (more) affordable polymer material innovations.

4.2. "Overengineering": Implications and Causes

In general, most experts emphasized the barrier of overly high material requirements by admitting that

> "*[w]e have to ask ourselves if the specifications have not reached a level by now that corrective measures can be taken without sacrificing overall quality*" (Interview 71).

In accordance with the quantitative results shown in Table 1, the experts regard the implications for the use of secondary materials as critical since

> "*[w]ith excessive quality specifications and self-created complexity, we slow ourselves down to try out new [sustainable] ideas*" (Interview 58).

Using an iterative coding procedure commonly applied in qualitative research [39], we found that the *causes* of overly high requirements can be classified into three main categories.

First, *individual* causes include risk averse behavior towards reduction and personal identification with the status quo. In that sense, one expert stated that

> "*[t]he technical specifications create a fixed point from which it is difficult to deviate. It can partially pull you back to something that is perceived to be safer*" (Interview 57).

Second, *collective* causes are defined as an inert organizational culture of perfection and shared perception of being quality-driven, an unpleasant management of failures as well as the unique selling proposition in high-quality segments. E.g., an interviewee shared that

> "*[s]pecifications such as a density of 1.2g/cm^3 are [...] not relevant to customers*" (Interview 36).

Third, *procedural* causes include the lack of methods and tools that allow effective requirement differentiation depending on the application of the materials as well as path dependent behavior within development teams. One interviewee explained that

> "*[s]pecifications should not be derived from past technical knowledge of the best material available on the market – thus forcing the market to meet ever higher requirements – but realistically based on what is needed and used*" (Interview 46).

In addition, another challenge occurs that is also closely linked to the academic discussion of FE. During the development process, materials are rejected because they either do not meet the overly high technical requirements or because (supposedly) better alternatives are available. It is not sufficiently considered whether the rejection is justified if eventually a non-best-in-class material also fulfills the requisite requirements of the respective application or use case. Thus, secondary polymers are rejected, because they cannot reproduce the virgin material quality [4, 5] and are therefore regarded as inferior (despite fulfilling the requisite requirements for V&V purposes).

Consequently, we argue that innovation principles that search for the (technologically) best-in-class materials may not be supportive for the implementation of secondary polymers. The need for a critical review of a product's underlying requirements becomes necessary *before* it is optimized through life cycle engineering approaches. The emphasis of our method is therefore primarily on the *effectiveness* of requirements rather than on environmental improvements of a product that has passed all V&V steps. With this in mind, the solution-oriented part of the paper will be introduced, using the approach of SE as described above.

4.3. Perspectives on Frugal Engineering

Various methods in product development help to define abstract material requirements resulting from stakeholder demands, such as customer needs or regulatory constraints. In the context of the action research project, system orientation as described in subsection 2.2 has proven to be particularly valuable, as it implements the core concepts of FE in a systematic manner. The main focus of the action research project was to identify which requirements are needed at which level, i.e., determine at which level requirements become too high and can therefore be reduced in order to engineer products with an *optimized* performance level [12].

Two different approaches, top-down and bottom-up FE, were developed using the V-model approach, see Fig. 2. The focus in the context of sustainable FE is therefore primarily on the effective differentiation of requirements (left side of the V-model) and the corresponding validation procedures, which will confirm whether the verified (sub-)systems meet or exceed the stakeholder requirements.

4.3.1. Top-Down and Bottom-Up Frugal Engineering

As shown in Fig. 2, top-down FE commences with the stakeholder requirements and gradually determines the necessary technical requirements at the individual (sub-)system levels. This ensures that material requirements – in particular for new (vehicle) projects – are individually adapted and do not follow a copy-paste strategy from previous projects that may conflict with FE. Engineers and product developers need to ask which *types* of requirements are demanded so that the developed system can be validated against stakeholder needs in a later step.

The requirement of heat aging of polymers serves as an illustrative example. If a customer demands long-term quality, e.g., means that materials do not become brittle even after years of thermal stress, this demand results in a requirement for heat aging resistance of the polymer. As heat aging resistances can be ensured and tested using a variety of possible requirements and subsequent verification measures (temperature, stress duration, humidity etc.), bottom-up FE becomes important.

Although top-down FE can determine which general requirements are necessary for system validation, the *appropriate level* of these requirements remains unclear, so that, e.g., component requirements can exceed what is required on a higher (sub-)system level. Therefore, as indicated by the right arrow

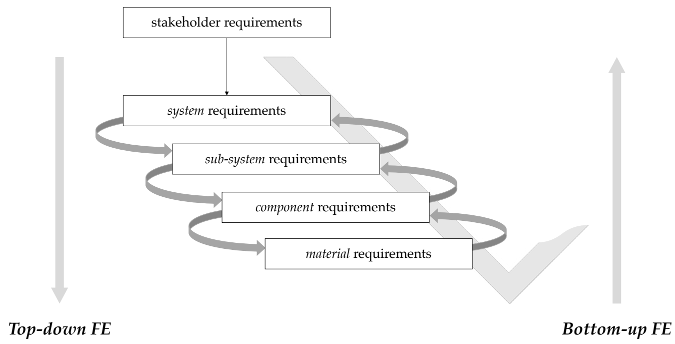

Fig. 2. Top-down and bottom-up FE as part of the left side of the V-model

in Fig. 2, bottom-up FE challenges whether a lower-level requirement exceeds what is needed for a validation of a higher (sub-)system level.

With regard to the above example, a verified heat aging requirement of 1000h at 150°C leads to a validation against stakeholder needs (i.e., no embrittlement after years of thermal stress). Nevertheless, a lower requirement of 200h or 400h at 150°C might also lead to a validation, resulting in less polymer additives or a higher possible percentage of secondary material. In this context, a *reduction-oriented validation perspective* has proven to be helpful. What happens with a higher-level requirement when any lower-level requirement is reduced? Is the higher-level requirement still fulfilled? Is it possible to validate the higher-level (sub-)system with the reduced lower-level requirement?

4.3.2. System Orientation: An Enabler for Frugal Engineering

Top-down and bottom-up approaches demonstrate that system orientation represents one way to implement FE and to determine the requisite performance level at which a system can still be validated. Any further reduction cannot lead to validation because stakeholder needs are not met any longer. Thus, if a product is perceived, e.g., as low-quality, either the underlying assumptions of the customer requirements were wrong or reductions were made that led to a system that was no longer valid against the market needs. In a similar vein, if material performances can be reduced and the overall system is still valid against stakeholder needs, the former required performances must be regarded as *overengineered*.

Technologically inferior secondary polymers are given a new opportunity to be implemented, since engineering principles are explicitly linked to market-oriented use cases instead of technology-oriented material properties. Using the proposed reduction-oriented validation, engineers and product developers can also rely on non-best-in-class materials since any lack of functionality or material performance is detected early in the innovation process at low-level systems.

Moreover, material requirements can be revised according to the presented approach, thus realizing an optimized performance level in an iterative way instead of demanding too high, unrealistic and too complex requirements that inhibit the transitions towards the usage of secondary polymers.

5. Conclusion and Limitations

In this paper, we have illustrated that excessively high requirements can indeed represent a serious barrier to the implementation of secondary polymers in the automotive industry. We found that the effectiveness of material requirements is of particular importance for the optimization of existing products from an economic and ecological perspective. By implementing FE principles engineers and product developers follow a market-oriented good-enough logic instead of a technology-driven best-in-class logic. Inspired by SE, two new approaches, top-down and bottom-up FE, have been discussed that facilitate the creation of suitable and use-case-oriented material requirements as well as support the revision of existing requirements.

Using top-down and bottom-up FE, a coherent interconnection is created between stakeholder requirements and abstract material requirements. Effective differentiation of requirements supports the use of often technological inferior secondary polymers and encourages engineers to use materials that are not best-in-class but meet the requisite requirements of the use case. Further, system orientation ensures that other efficiency approaches carried out as part of life cycle engineering, such as decarbonization measures of polymers, do not optimize an overengineered system.

Limitations of the research are to be seen in the narrow scope of the automotive material development within one company. To improve the generalizability of the research it is therefore necessary to include other companies, industries and data that extend the expert scoring and interviews conducted for this study. Likewise, the possibilities for iterative development in a hardware-driven domain are limited, so that the search for the "*frugal golden mean*" must be considered as a long-term process and is ongoing from (vehicle) project to project.

Additionally, the narrow focus on material performances has to be emphasized. Other constraints in product development, such as cost advantages due to economies of scale or marketing considerations, equally influence the selection of (secondary) polymers.

Acknowledgements

The authors would like to thank Volkswagen AG, in particular the organization of materials development (EGMP) in Wolfsburg, Germany, for supporting the action research project.

Appendix A. Interview Guide

(A) Are certain barriers or issues not (sufficiently) addressed in the previous ratings and should therefore be added?

(B) What do you consider to be the main reasons why the internal requirement management and technical specifications are a barrier for the implementation of secondary polymers? (In case of disagreement – for what reasons do they not constitute a barrier?)

(C) Based on your experience and on a deeper level, what are the reasons why the implications just mentioned in (B) exist? What are (not) the causes of the barrier ”requirement management and technical specifications”?

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