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PROCESS INTEGRATED PRODUCT CONCRETISATION: EXTENDING CONCEPTUAL DESIGN WITH FUNCTION FOCUS BY PROCESSUAL PRODUCT DESIGN

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Abstract

Existing development approaches usually focus on the product function as the starting point of development activities, since function fulfilment is the main carrier to ensure stakeholder satisfaction with the technical product. However, the early anticipation of technical processes provides huge potential to develop technical products with better product properties that e. g. tap potentials of new manufacturing processes or realise a resource-sensitive design. Product designers face the challenge of finding possible solutions that realise the product function and holistically match the intended product life cycle processes. Therefore, the paper extends the functionally focused development process by property-based product modelling in the process context to systematically tap potentials of entire product life cycle processes. Desired properties and desired factors harmonise the different structures between requirements and solution finding in function and process context. Thus, the Extended Mapping Model provides a valuable base for methodological support for a holistic process integrated product concretisation in context of the entire product life cycle processes.

Keywords: Conceptual design, Early design phases, Integrated product development, Design process, Process modelling

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1 INTRODUCTION

1.1 Motivation

Customers have many expectations of a technical product that is being developed. These expectations are documented by designers as *requirements* in requirements lists (Pahl et al., 2007). In times of limited and shrinking worldwide resources, the resource-sensitive development of technical products becomes increasingly important. Resources are consumed in the technical processes of material production and manufacturing. They are also recovered in recycling and disposal processes. In addition, all *processes of the product life cycle* have environmental impacts - especially the use phase (Figure 1).

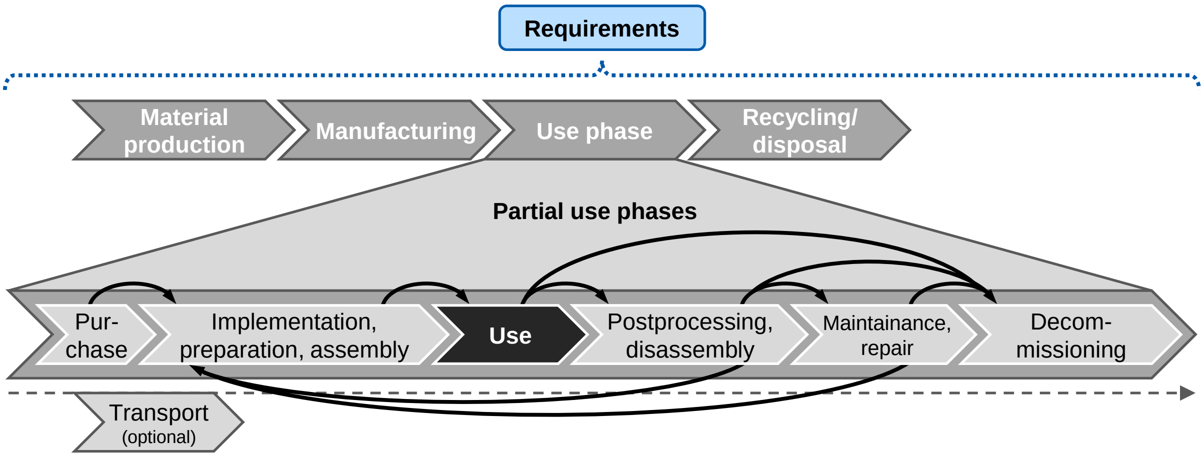

Figure 1. Resource-sensitive processes during product design; adapted from Dannheim (1999) and Oberender (2006)

Requirements that result from the technical processes of the product life cycle *(process requirements)* have the greatest influence on resource-sensitive product design. These requirements influence product quality, which is directly perceived by the customer (Haberfellner et al., 2015). The prediction of product life cycle processes and their early anticipation in product design becomes a necessary prerequisite to save resources while ensuring function fulfilment during product use (Figure 2). The key question in successful product design is: Which properties does a technical product have to have to tap the process-specific potential of every product life cycle process while meeting requirements for function fulfilment? Product designers act in a huge and dynamic field dominated by changing processes, new technologies and different stakeholder expectations.

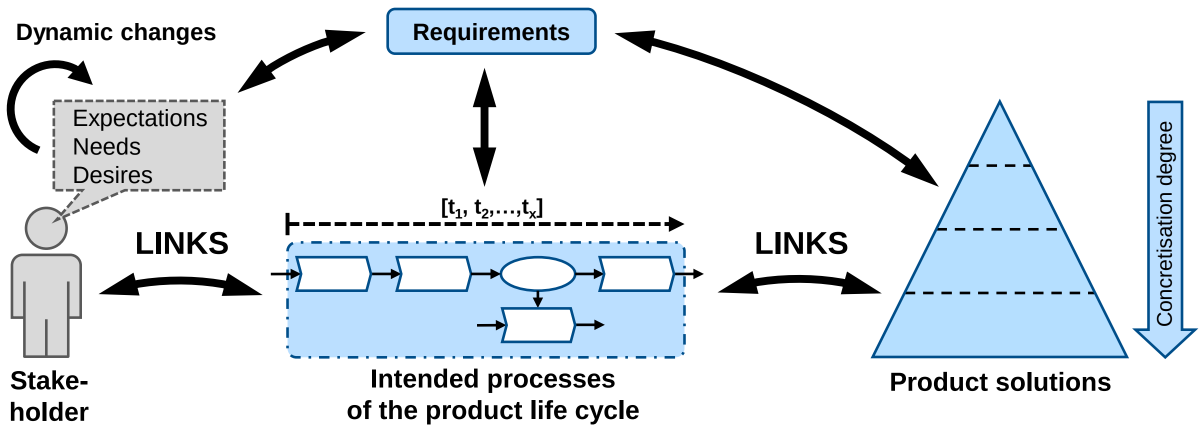

Figure 2. Links between requirements, stakeholder, product and process development; adapted from Mattmann et al. (2016)

1.2 Purpose and structure of this paper

The influence of process requirements is not easily predicted. Unfortunately, technical processes and the technical product to be developed have bidirectional impacts which are considered late in conventional product design. The potential of technical processes to meet function fulfilment is not met, while process-specific influences on the technical product to be developed are considered.

Based on a systematic *literature review* of established development approaches (Section 2), this paper extends the predominantly function-oriented product design with process-oriented product design. This paper proposes a *new framework* to develop technical products in their function and process contexts equally to tap process-specific potential during the early phases of product design (Section 3). The proposed framework provides the basis for support of product designers during early design phases. The results of process analysis are used to derive process requirements in order to anticipate information on technical processes as early as possible when developing the technical product in its process context. The new framework can be used in all phases of the product life cycle to focus on function fulfilment and to consider process-specific aspects as early as possible during the development process. The potential of the novel development framework is shown in a *case study* (Section 4). It will ensure resource-efficient product design and realise manufacturing and use potentials.

2 BACKGROUND

Existing development approaches usually focus on product function, since function fulfilment is the main driver of stakeholder satisfaction with the technical product. However, the early anticipation of technical processes creates huge potential to develop technical products with better product properties that could, realise the potential of new manufacturing processes or resource-sensitive design.

2.1 Consideration of technical processes and requirements

Most development approaches focus on one aspect of a three-dimensional classification scheme that distinguishes between activity-based, solution-based, problem-oriented, solution-oriented, and prescriptive and descriptive design processes (Wynn and Clarkson, 2005). Integrated design processes cover more than one dimension of the classification scheme. They describe development processes holistically. Most development approaches combine different views of the classification scheme, whether the design process is described prescriptively or descriptively, and whether they focus on systematic task clarification to ensure that problems are well-defined to enable solution finding or are solution-oriented beyond conceptual design.

However, these approaches do not answer the key question of how requirements and product properties are interrelated, which ensures product design that incorporates properties that enable function by tapping the full potential of new manufacturing processes or processes of the product life cycle. The synthesis of new products is mainly initiated by goal formulation (determining what should be developed) from the designer's principal solution ideas (Pahl et al., 2007). Synthesis goes along with analysis, where behavioural properties of the technical product are predicted from known construction product properties. Goal formulation has to be considered throughout the entire design process (Pahl et al., 2007). Key factors for market success of products developed are mainly around clarification of design tasks to define essential and construction product properties that the intended product should have, according to predefined or required properties. The technical product is incrementally designed and is composed of a variety of solutions for specific sub-problems. Figure 3 illustrates the results of a systematic literature review, in which established development approaches have been classified according to their integration of requirements and technical processes into the development process. The classification should not be seen as a comparison of each development approach, since each development approach focuses on different aspects of the development process. The classification scheme visualises how each development approach deals with requirement and process integration in varying degrees.

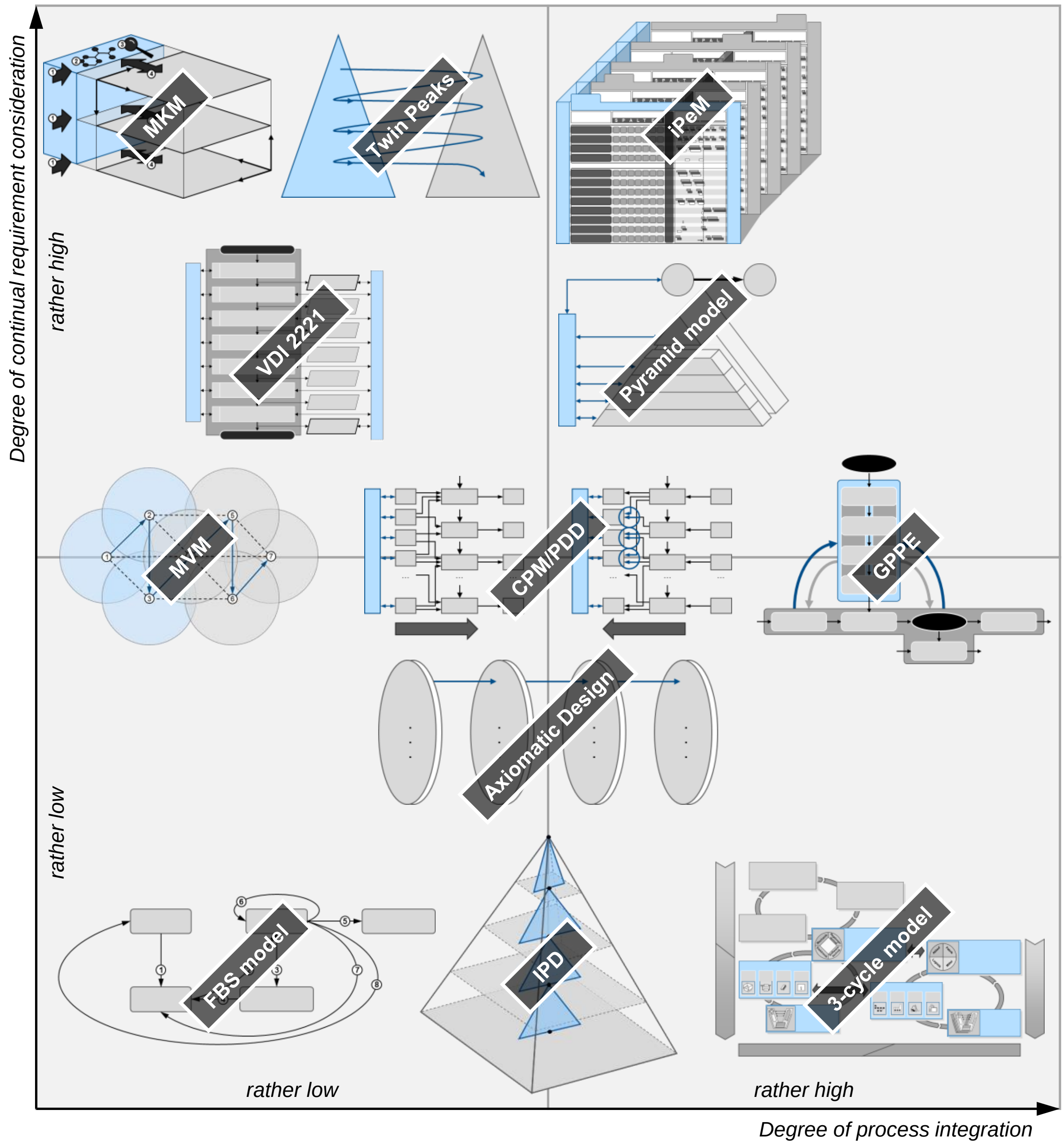

Figure 3. Classification scheme of development approaches in literature

As in the sequential approach of Pahl et al. (2007), the VDI guideline 2221 (1990) focuses on requirements that are documented in the requirements list as the foundation of design processes. Both design models consider the potential of manufacturing technologies late in the design process. The FBS model (Gero, 1990) and IPD (Ehrlenspiel and Meerkamm, 2013) highlight technical solutions for function fulfilment. Process-specific influences of manufacturing technologies are considered during embodiment.

Common models, like CPM/PDD (Weber, 2005) and Axiomatic Design (Suh, 1998), focus on different perspectives of systematically map requirements to product properties. The aim of CPM/PDD is to match product properties to properties demanded by customers. This is done by using analysis and synthesis steps, where characteristics and their values are defined during synthesis to achieve the demanded properties. Care has to be taken, since these approaches use different terminology for requirements and product properties to the conceptual understanding in Birkhofer and Wäldele (2008) and this paper. Axiomatic Design is the formalised development of technical systems. Two major questions characterise Suh's Axiomatic Design: "What do we want to achieve?" and "How do we choose

to satisfy the need?" They are used to transform customer attributes in the customer domain into functional requirements and constraints within the functional domain (Suh, 1998). These functional requirements have to be realised by design parameters. Process variables characterise appropriate manufacturing processes that physically realise the defined design parameters. Since each domain is mapped to the next one, customer attributes are always considered during the detailed design process.
The 3-cycle model (Gausemeier et al., 2012) integrates the planning of production processes into the development process; other technical processes of the product life cycle are not. This issue is solved by holistic models, like GPPE, in which technical products are developed holistically along with their anticipated processes (Anderl et al., 2007). Decisions made in the development process influence both the technical product and the technical processes of the product life cycle.
The pyramid model (Sauer, 2006) puts technical processes first and highlights the dynamic interrelations between process development realised by procedures and product development at different levels of product concretisation. These two development areas are holistically connected by requirements. MVM (Lindemann, 2009) and MKM (Ponn and Lindemann, 2011) both highlight task clarification as the initial step in defining product structure. However, processes have a low priority in the development process. The same applies in the Twin Peaks model (Nuseibeh, 2001), which focuses on dynamic interrelations between requirements and defined system architecture, in contrast to other development approaches.
iPeM describes a meta-modelling of tripartite systems in different layers (Albers et al., 2016). Requirements, restrictions, dependencies and relations between requirements are modelled within the target system. Actions within the action system describe all activities that transform the target system into the object system in which the developed product is modelled and described (Albers et al., 2005). The product, validation system, production system and strategy layers of iPeM ensure not only process-specific product development but also the development of technical products in different product generations.
However, these models do not focus on processes that have to be developed in tandem with product design to ensure products that best fit their appropriate processes, such as use processes and manufacturing processes. They demand continual and dynamic update of requirements while only a few support documentation of requirements along the entire development process and the resolution of contradictory and conflicting requirements. These models do not consider the detailed relations between requirements and defined product properties of the technical product that emerge continually due to decisions and determination of specific solutions during the entire development process.

2.2 Similarities of solution finding in process and function contexts

Existing models of design processes focus on the correlations between requirements and the development of technical products in function and process contexts. Since solution finding in function and process contexts has major similarities to their underlying product and process models (Gramlich, 2013), both views can be united in a shared requirements model (Figure 4).

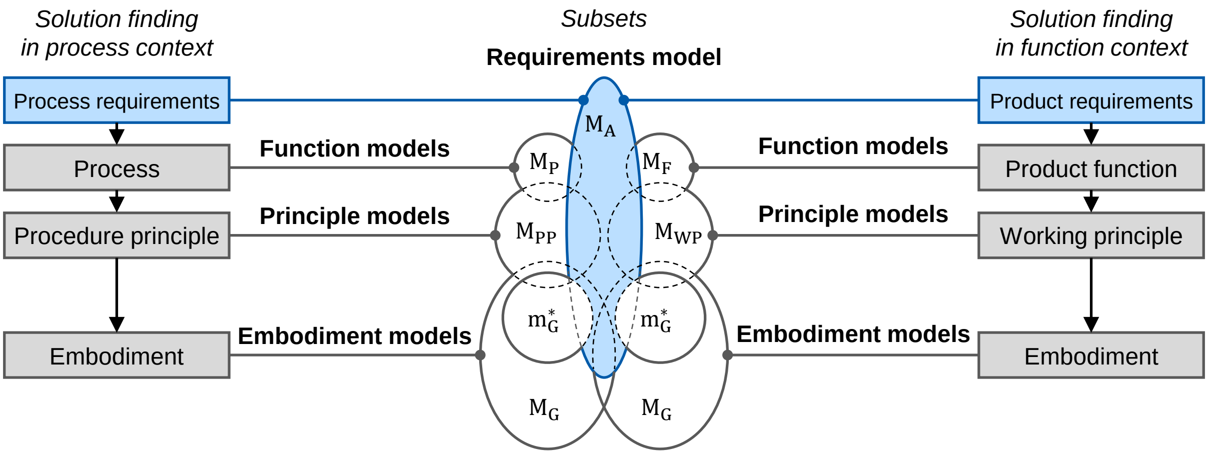

Figure 4. Venn diagram of subsets in solution finding processes

The similarities between product modelling and process modelling shown by using a property based product and process description show that all of the models used in design processes are linked to the requirements model. Thus, product and process requirements in the requirements model have to be considered throughout the entire development process. Optimal product and process solutions are characterised by the subset of properties that a technical product has to have in its function and process contexts.

Technical processes are defined as the transformation of objects from an initial state to their final state. The object has properties; technical processes lead to a change in properties of the objects. Besides the interaction between the user and the technical process, the technical process interacts with the system environment and uses available resources for the transformation of the operand.

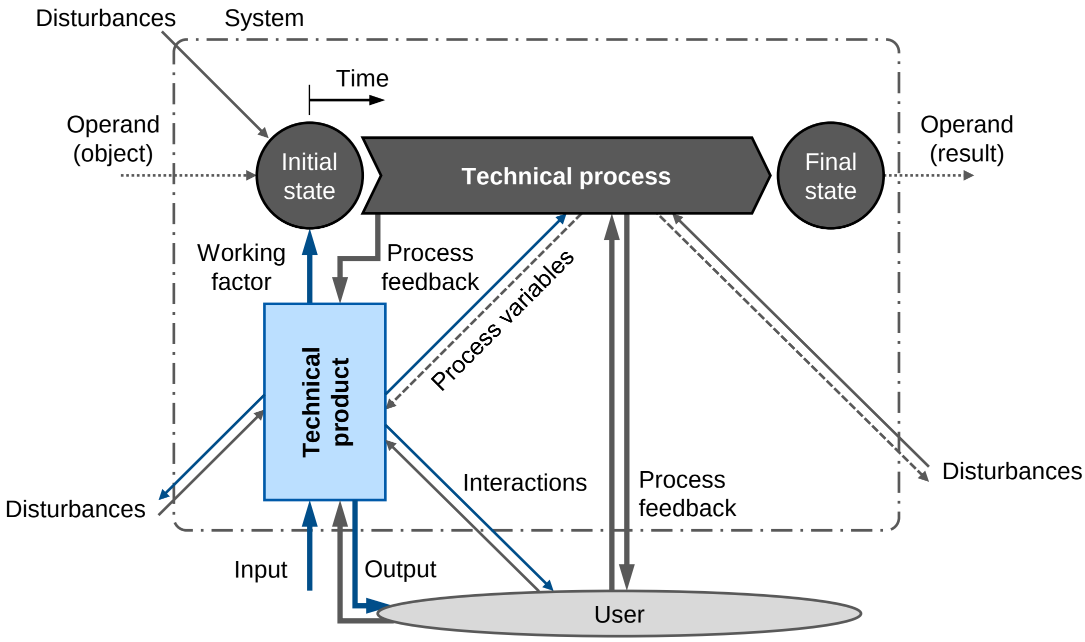

Figure 5. Extended process model, as in Kloberdanz et al. (2009)

Procedures realise the technical process (Sauer, 2006). Thus, the working factor has to be provided through function fulfilment by the technical product to realise the technical process according to a specific procedure. The anticipation of technical processes of the product life cycle leads to major information about each element of the process model. Thus, *process requirements* contain anticipative information about the intended behaviour of the technical product in its specific technical process. They implicitly define what product properties the technical product has to have to realise the intended process, either as operand or as the operator. Thus, process requirements describe each element of process modelling (states, interactions, process variables, inputs and outputs). This information has to be transformed into product requirements to develop the best technical product for the intended technical processes.

3 EXTENDED FRAMEWORK FOR PROCESS-RELATED PRODUCT DEVELOPMENT

Technical products have to have properties that best fulfil the acquired requirements. Particularly in the early phases of product design, the influencing possibilities are high when limiting costs (Ehrlenspiel and Meerkamm, 2013). Thus, anticipated process information has to be considered during conceptual design of technical products to ensure the best determination of product properties in the continual concretisation process.

3.1 Mapping Model in the function context

The modelling of technical products for function uses partial product models at each level of product concretisation: function models, effect models, working principle models and embodiment models (Figure 6). The Mapping Model, in its original description (Mattmann et al., 2016), leads to consolidated, incremental, property-based product design by harmonising requirements and product properties at each level of product concretisation. The technical product developed is described at each level of the product model pyramid by its dependent and independent product properties (Birkhofer and Wäldele, 2008). However, the technical product is modelled and described by only properties, based on its product function.

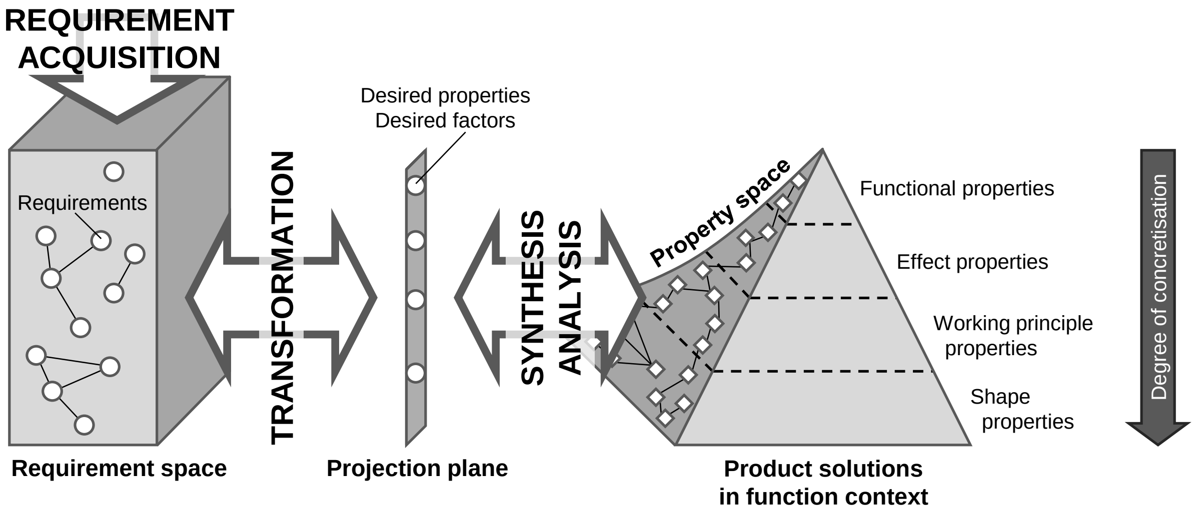

Figure 6. Mapping model for product and process development, from Mattmann et al. (2016)

Although designers define product properties continually during product design, they think implicitly in models that are directly related to product properties. Product models provide the structure of product properties. Product properties, as modelled in the property space, allow designers to evaluate how good a technical product is compared to other competing products. During development processes, designers face the challenge of determining independent product properties that best influence dependent product properties, based on stakeholder expectations. Based on various levels of the product model, properties of function, effect, working principle, and shape are all differentiated. Structural and element properties are focused at each level (Gramlich, 2013). Requirements are semantically interrelated, and are either partially in conflict or contradictory. Product properties also consist of a characteristic and an appropriate value (Lindemann, 2009) that are conflict-free. Therefore, desired properties and quantities are semantically equivalent to requirements, can have multiple values for each characteristic, and are matched to the different degrees of concretisation of product modelling in one-to-one connections. They provide the fundamental basis for analysis and synthesis activities in the development process since they represent dependent product properties that are perceived by the market or customer.

3.2 Extended Mapping Model by process-related product modelling

The Mapping Model focuses on the technical product and its product function during the development process to find function-related solutions. However, since the technical product acts in processes of the product life cycle as operand or operator, the influence of these processes has to be anticipated in the development process. This leads to a major extension of the development process, in which technical products are developed equally for both their function and process contexts. While addressing the issue of which function-required product properties the technical product has to have, product designers also have to assess which process-required product-properties the technical product are required to guarantee realisation of the intended product life cycle processes.

Figure 7 shows the Extended Mapping Model of incremental property-based product design in the context of product life cycle processes.

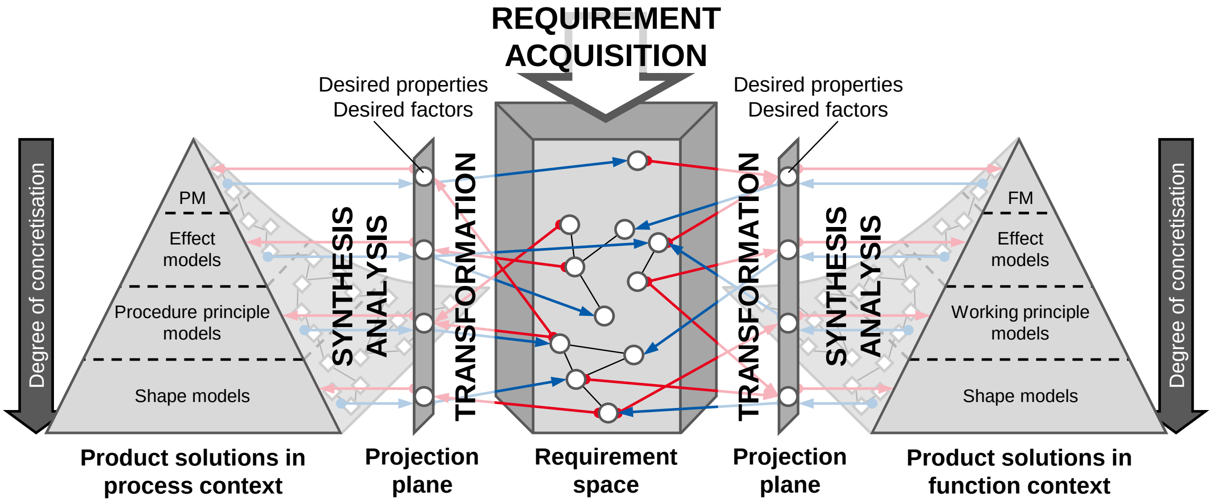

Figure 7. Extended Mapping Model for integrated product and process development, based on product properties

As highlighted by the Extended Mapping Model, designers differentiate between two ways in which the technical product is holistically developed: the technical product in its role as the operand in technical processes of its product life cycle; and the design-related part of development activities that focus on the intended product behaviour during use because of function fulfilment. Since every decision made in design processes is based on requirements, the requirements space is at the centre of solution finding in both function and process-related contexts.

The Extended Mapping Model is based on three major spaces: requirement, solution, and property. These three spaces are highly interrelated and are connected by the projection plane which captures the structure of the solution space, thus enabling the systematic mapping of semantically structured and clustered requirements to the property-based description of product concretisation (Mattmann et al., 2016). The major advantage of desired properties and factors is their harmonisation of structures between the requirement space and the solution space (Mattmann et al., 2016). Modelling of technical products in the process context uses process models, effect models, procedure principle models and shape models. Every process is realised by an appropriate procedure principle (Sauer, 2006). The technical product has to have specific process-relevant properties to act as intended in the product life cycle process. All process-relevant solutions are linked to requirements. Similar to the development of the technical product in its function context, the projection plane harmonises the structures of the requirement space and the solution space. Desired properties and factors refer to function modelling in the case of process modelling to process-relevant properties. These properties are essential for process design and product design throughout the entire product life cycle processes. Matching function-required properties to process-relevant properties leads to a conceptual product design that is predestined for function fulfilment while best realising process-specific potential.

4 CASE STUDY

The development of a multifunctional linear system using the manufacturing technology of linear flow splitting and linear flow bending can be used for various applications, like a multifunctional façade cleaning system (Figure 8). Such technical products are conventionally realised by various manufacturing technologies that are sequentially applied in the manufacturing process chain. The case study shows the potential of mapping requirements to properties in function and process contexts using the Extended Mapping Model. The technology-pushed design approach reduces the number of separate manufacturing processes by adding functionality to the technical product and by ensuring cost-efficient realisation (Lommatzsch et al., 2011) with reduced production effort when the number of linear bend split bifurcations is low. The linear system is manufactured in continuous flow production, which reduces manufacturing effort while including resource-sensitive design.

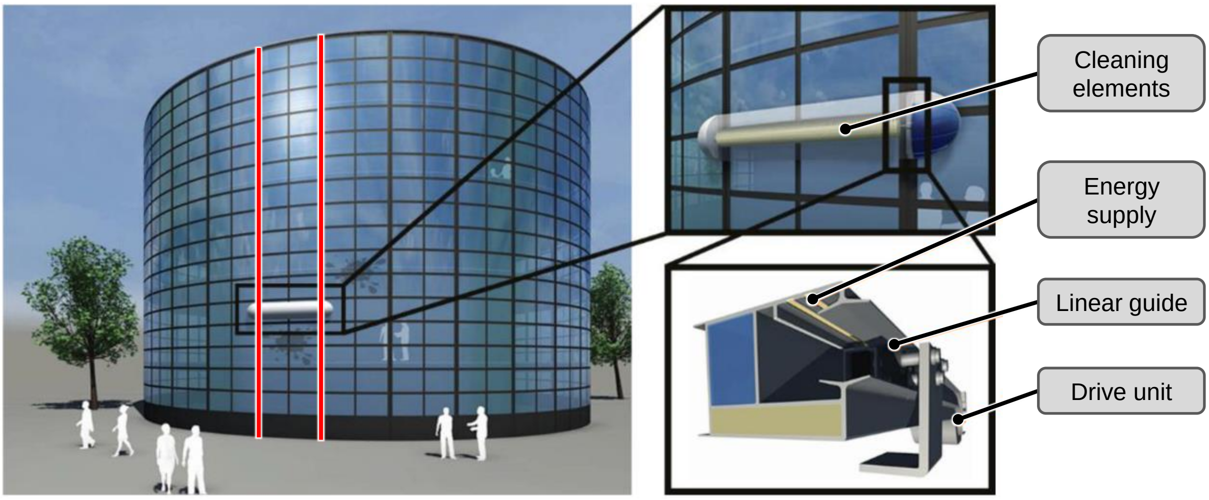

Figure 8. Product idea of a multifunctional linear system (Groche et al., 2017)

The anticipative process analysis of manufacturing, use and recycling processes results in a variety of process requirements. Linking requirements to desired properties and factors enables the identification of conceptually relevant characteristics for the development of the multifunctional linear system. The requirement of preventing human contact with the moving parts of the façade cleaning system leads to the desired property of an undercut in the linear guide. The maximum load capacity of 15 kilograms leads to force-specific properties of the working factor, like the type of energy, the working direction and the magnitude, in order to maximise the bending stiffness of the linear guide.
Providing contact pressure for mechanical cleaning is a requirement. This leads to the collection of information on the contact pressure of cleaning elements that are responsible for the appropriate cleaning result to save resources, like water and energy, during the cleaning process. Further safety requirements demand the prevention of the motion system from stopping when there is an energy shortage. Thus, the holding force of the motion system has to be greater than its weight force.
The systematic link between requirements and desired properties/quantities in function and process contexts enables the equal concretisation of the technical product. Based on the desired properties identified, algorithm-based solution finding, using mathematical optimisation methods, was used to realise optimal product geometry and topology of the linear guide while saving resources and effort due to anticipated manufacturing and use processes.

5 CONCLUSION AND OUTLOOK

This paper demonstrates the need to extend the function-focused development of technical products to realise process potential. The Extended Mapping Model enables the systematic link of process requirements to product properties that have a major influence on the customer perception of quality. The potential of technical processes in every process of the product life cycle can be integrated into the development process, since each process can be modelled with solution elements in separate process domains.
This approach, as shown in the Extended Mapping Model, leads to new and innovative products that realise the full potential of product life cycle processes in the early phases of product design. Their process-relevant properties are directly integrated into the defined property networks to achieve the best possible conceptual designs that realise the potential of manufacturing technologies and function fulfilment in use processes while guaranteeing resource-sensitive design. Further work will focus the modelling of technical products in the context of their procedure principle models to close current gaps between conceptual design and embodiment of technical products in the process context.

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