THE MALICIOUS LABYRINTH OF REQUIREMENTS - THREE TYPES OF REQUIREMENTS FOR A SYSTEMATIC DETERMINATION OF PRODUCT PROPERTIES

Mattmann, Ilyas; Gramlich, Sebastian; Kloberdanz, Hermann
Technische Universität Darmstadt, Germany

Abstract

Product designers face the challenge of translating customer needs and expectations into requirements to define appropriate desired product properties that satisfy customers. Various conceptual requirement definitions are existing in literature. The definitions allow a great room for interpretation and are partially contradictory for which reason it lacks a differentiated conceptual understanding.
Therefore, the paper presents the results of a systematic literature analysis of existing requirement definitions by analysing their causal dependencies. Often, the terminology refers to the purpose of requirements in development processes. The paper provides a critically reflected conceptual differentiation of existing requirement terms. Resulting from the differentiated conceptual understanding, three major types of requirements need to be distinguished. They support an effective transformation of requirements into desired product properties. Thus, a valuable base for methodological support of the requirement acquisition process is provided.

Keywords: Requirements, Early design phases, Product properties, Conceptual definitions

Contact:
Ilyas Mattmann
Technische Universität Darmstadt
Fachgebiet Produktentwicklung und Maschinenelemente
Germany
mattmann@pmd.tu-darmstadt.de

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1 INTRODUCTION

Product designers face the challenge of determining product properties during the development of technical products to meet customer needs and expectations that are indirectly formalised as requirements. Unfortunately, there is no differentiated requirement terminology. Most product designers get lost in the malicious labyrinth of requirements (Figure 1), which leads to a critical confusion about requirements and desired product properties, since customer needs and expectations have to be formalised into requirements to systematically determine desired product properties.

Various authors have proposed a range of conceptual requirement definitions, concerning an undifferentiated understanding of *requirements, specifications, desired product properties, needs, expectations, demands, wishes, desires, problems, goals, objectives, constraints, boundary conditions* and *restrictions*. Even existing definitions are too vague, allowing great room for interpretation.

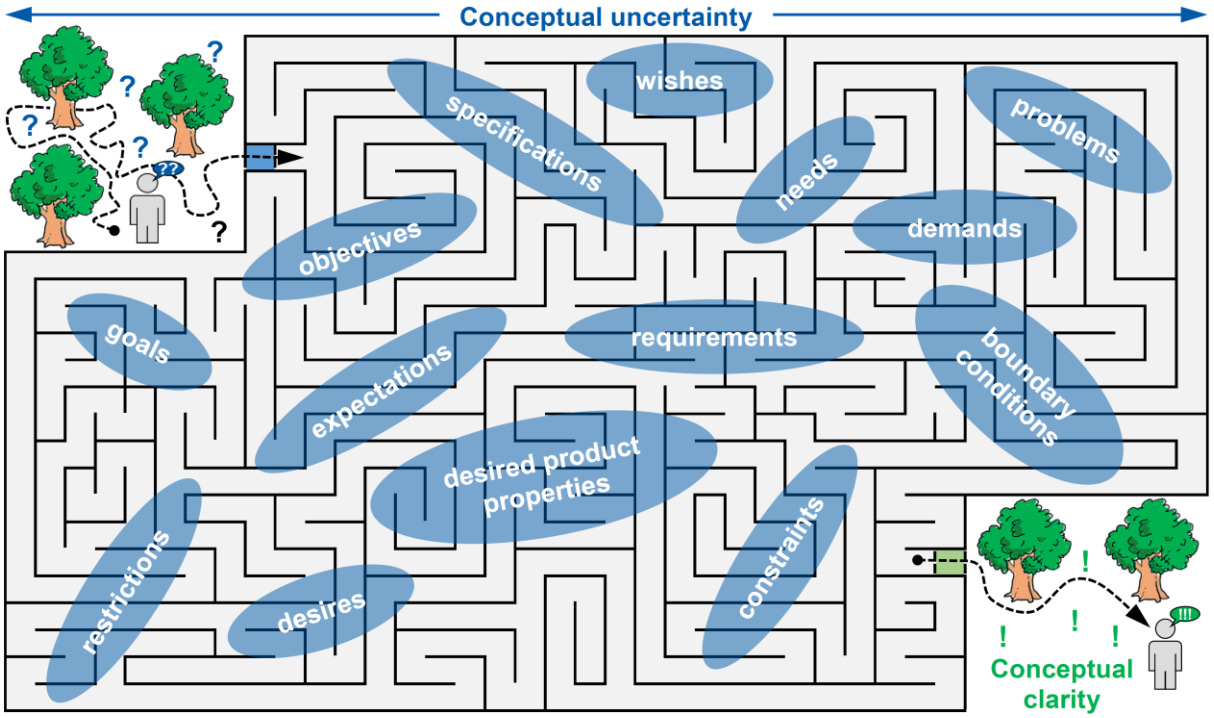

Figure 1. Labyrinth of conceptual requirement definitions

Above all, conceptual requirement definitions have content overlaps and are partially contradictory. Product designers are thus impeded during a systematic and purposeful determination of product properties according to underlying requirements, since there is no common conceptual base for ensuring qualified methodological support. An effective translation of vague customer needs and expectations into product design is stressed, since formalised and specified requirements have to be fulfilled during the product development process. Unfortunately, requirements and desired product properties are not clearly distinguishable, according to the written conceptual definitions in literature.

Therefore, a systematic and differentiated conceptual understanding of requirements is needed to provide an established understanding of requirements with no competing or contradictory meanings, supporting product designers with efficient and methodological support during the requirement acquisition process.

In general, it is difficult to interpret customers' deepest needs and desires that they feel and perceive. Product designers have to extract the essential requirements by interpreting customer needs (Ulrich and Eppinger, 2008) and desires, while defining the desired product properties according to underlying requirements. Product designers have to understand the desires and needs of customers and systematically interpret them to guarantee formalised (Feilden, 1963), and sufficient, qualitatively good requirements documentation in requirements lists.

These considerations become relevant to the development of technical products when granting customer satisfaction with the technical product. Technical products should have specific product properties to guarantee best fit with the customer's desired product properties that meet their needs, which leads to

high satisfaction during use of the technical product. A fundamental base of requirements is indispensable in the outcome of development projects (Chakrabarti, 2002).
This paper is structured as follows: The *results of a systematic literature analysis* of existing conceptual requirement definitions brake through the labyrinth of conceptual definitions. Based on the analysed conceptual definitions, the huge variety of conceptual definitions is systematically differentiated to provide a *clear and established conceptual base*. This is achieved by showing the relationships between the most important requirement terms. Based on the critical literature analysis and the differentiated conceptual definitions, *three major types of requirements* are identified to support product designers during the highly complex process of requirement acquisition. The introduced types of requirements are demonstrated using the development of a wooden balance bike, which highlights the link to the *property-based description of technical products* to guarantee customer satisfaction. The paper finishes with *benefits and conclusions*.

2 BREAKING THROUGH THE LABYRINTH OF CONCEPTUAL REQUIREMENT DEFINITIONS

Requirements build the initial base of every development project. Customer needs and desires must be captured and translated into requirements to develop marketable technical products. The term requirement is diversely defined in scientific literature. Attributable to this, nearly every product designer is lost in the labyrinth of requirement terminology. Unfortunately, there is no differentiated understanding of the terms in the context of requirements.
The following conceptual definitions are adapted and partly translated from literature. Generally, as remarked by *Pahl et al. (2007)*, there are still translation issues in the specific terminology. Many authors use slightly different terms, which makes it difficult to get consistency across the terminology used. Nevertheless, this paper uses consistent terminology adapted from the German systems of concepts.

2.1 Lost in the labyrinth of conceptual requirement definitions

The literature analysis of existing definitions shows that the analysed definitions can be subdivided into five significant categories, as shown in Figure 2.

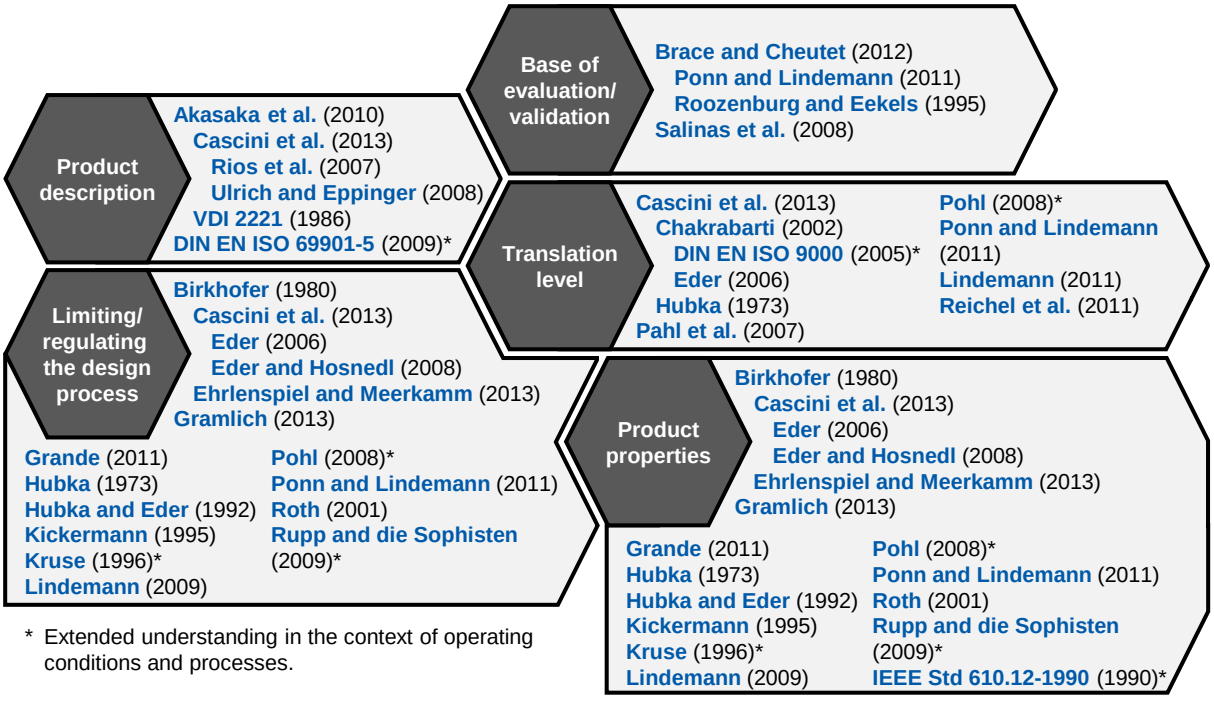

Figure 2. Requirement definitions categorised according to their purpose

Each category describes the specific purpose of requirements during the development process. However, the categories are defined in terms of the substantive meaning of each conceptual requirement definition. Thus, one conceptual definition may fit in more than one category, according to the appropriate purpose that is pursued by requirements in the development process. Each category reflects the main focus of

the written definition. The conceptual definitions of requirements refer to their specific purpose during the development process, according to the:

- **description of the technical product** to be developed
- **translation level** for the translation of customer needs into formalised requirements
- reference to **product properties** for modelling and describing technical products
- basis for a structured **evaluation process** during the development of technical products
- systematic **limitation** of possible solutions by constraining the **design process**

2.2 Requirements aiming at the description of technical products

This first category subsumes the purpose of requirements for the description of technical products. *Akasaka et al. (2010)* emphasise that requirements precisely describe the technical product due to their increased formalisation degree. In this context, requirements define specified characteristics or specifications of the technical product. Since requirements represent information about the technical product according to the underlying product property concept, they are composed of a metric and the appropriate value (Cascini et al., 2013). This shows substantive overlap between categories. Although *Cascini et al. (2013)* refer to requirements as information about the technical product, they emphasise that requirements are equivalent to product properties highlighted due to the chosen documentation form.

Rios et al. (2007) define requirements according to a variety of quality criteria for the formulation and documentation of requirements. According to these quality criteria, requirements are naturally documented statements in written form, addressed to what the product should do and how the product function should be realised. This distinction is based on *Suh*'s axiomatic design theory (Suh, 2001). *Ulrich and Eppinger (2008)* define requirements very loosely, in contrast to the previously highlighted definitions. *Ulrich and Eppinger (2008)* and *VDI guideline 2221 (1986)* focus on the description of each aspect that concerns the function provided by the technical product, since a technical product fulfils its purpose by providing its product function (Gramlich, 2013). In contrast, *DIN EN ISO guideline 69901-5 (2009)* extends the common purpose of requirements to operating conditions and processes during the development of technical products.

2.3 Requirements aiming at the translation of customer needs and expectations into the formalised language of product designers

The second category refers to the translation of customer needs and expectations into formalised requirements.

As defined by *Chakrabarti (2002)*, *Cascini et al. (2013)* and *Reichel et al. (2011)* based on *Pahl et al. (2007)*, requirements represent the needs that are explicitly formulated according to gathered customer needs (Chakrabarti, 2002) and that influence product design. However, *Cascini et al. (2013)* and *Pohl (2008)* assume that requirements are product properties that are measurable and directly related to the needs of stakeholders (Cascini et al., 2013).

Pohl (2008) and *Ponn and Lindemann (2011)* place specifically formulated development goals under requirements, breaking down abstract development goals into specific requirements. *Eder (2006)* and *Hubka (1973)* have similar views, though they emphasise that requirements lead to the determination of product properties and are not equal to product properties.

Contrarily, *DIN EN ISO guideline 9000 (2005)* has great room for interpretation. The guideline places all requisites and expectations determined during the development process under the term requirement.

2.4 Requirements referring to product properties to model and describe technical products

The third category is by far the largest and most complex. The conceptual definitions of requirements refer to product properties for modelling and describing technical products. Even if the conceptual definitions directly refer to product properties in the context of requirements, they lack a differentiated conceptual understanding.

Birkhofer (1980), *Ehrlenspiel and Meerkamm (2013)* equate requirements with the desired properties of the technical product. *Birkhofer (1980)* references product properties to designer knowledge so that requirements are based on the product properties at each state of the ongoing product concretisation

process. The definition of requirements is carried out for hypothetical technical products. *Cascini et al. (2013)* emphasise that requirements are properties that may result from underlying needs.
Eder (2006), Eder and Hosnedl (2008), Hubka (1973) and *Hubka and Eder (1992)* stress the causal dependency for the determination of product properties. Starting from existing needs that stakeholders perceive, the totality of requirements is defined in a set of requirements that enables the determination of product properties (Eder, 2006).
Gramlich (2013) goes one step further. In his definition, requirements do not equal desired product properties. At most, requirements represent desired product properties. According to the modelling of processes, requirements may also address working variables (Pahl et al., 2007) and process variables. This essential enhancement shows that requirements are the main reason for assigning appropriate and desired values to specific characteristics according to the underlying property-based modelling and description of technical products.
Grande (2011) extends the concept of requirements according to technical product functionalities and qualities. Contrary to the previously analysed definitions, *Kickermann (1995)* refers to demands that may be fulfilled. Personnel resources, time resources and financial resources are taken into account to control the development process.
Rupp and die Sophisten (2009), the *IEEE standard 610.12 (1990)* and *Kruse (1996)* extend the definition of requirements to operating conditions and processes during the development of technical products, which is comparable to *DIN EN ISO guildeline 69901-5 (2009)*. According to *Lindemann (2009), Pohl (2008)* and *Ponn and Lindemann (2011)*, requirements represent technical development goals, respectively desired product properties. Several contradictory conceptual requirement definitions were found, even within one literary work.
According to *Ponn and Lindemann (2011)*, requirements are demanded product properties. Requirements are documented equally to product properties, according to characteristics and appropriate values. However, *Roth (2001)* stresses the causal dependency of requirements and product properties. Requirements lead to determinations that describe the desired product properties and additional conditions, including boundary conditions.

2.5 Requirements as the base for evaluation and validation in development processes

The fourth category addresses the purpose of requirements for the evaluation and validation of technical solutions in development processes.
Brace and Cheutet (2012) and *Ponn and Lindemann (2011)* refer to requirements as the specification of essential design evaluations. *Roozenburg and Eekels (1995)* distinguish requirements according to their meaning in the evaluation process. Requirements are objectives that every design proposal has to have. However, the wishes do not have to be met.
Salinas et al. (2008) define requirements very non-specifically. They mainly refer to requirements as the selection of possible variants and evaluation of technical solutions at different evaluation levels. If some variability is permitted or required, requirements indicate the direction and aim of optimisation (Roth, 2001).

2.6 Requirements for the systematic limitation of possible solutions by constraining the design process

This last category refers to the purpose of requirements that constrain the design process due to continuous consideration in selection and evaluation processes.
According to *Breeing and Knosala (1997)*, requirements are boundary conditions that must be considered during the development process to ensure the functionality of the technical product. Therefore, requirements constrain the entirety of desired solutions (Brace and Cheutet, 2012) by limiting the design process (Ponn and Lindemann, 2011). Their fulfilment controls the targeted course of the product development process and determines the product properties of the developed technical product (Kickermann, 1995).
Feldhusen et al. (2013) define requirements as restrictions that limit the possible solutions in the solution space. All Design for X (DfX) approaches are subsumed under requirements. Thus, requirements aim at restricting the development of technical products.

3 ACHIEVING CONCEPTUAL CLARITY USING DIFFERENTIATED REQUIREMENT TERMINOLOGY

The results of the literature analysis of conceptual requirement definitions show that five major categories exist, according to the purpose of requirements in the development process. The analysed conceptual definitions refer to requirements as demands, desired product properties and actual product properties of the technical product to be developed. They also refer to the description and representation of desired product properties that are determined by the ongoing development process.
As shown, there are differences in the definitions that nevertheless have commonalities. Since important terms are used synonymously and are not differentiated from each other, essential terms have to be strictly distinguished to provide a conceptual base during the development of technical products to support product designers methodologically during requirement acquisition.

3.1 Conceptual clarification of requirement terminology

Figure 3 shows the differentiated terminologies. Conceptual meanings should be used in product development to create differentiated conceptual understanding. To systematically consider customer needs and expectations during the development of technical products, it is important to distinguish between two major domains: the **customer domain** and the **design domain**.
Vague customer statements have to be translated into specified and formalised statements in the language of product designers to dertermine desired product properties during the entire development process. The key to every successful development process is this effective translation, as it guarantees customer satisfaction, building a valuable base for adjusting the development process to the defined and formalised requirements.

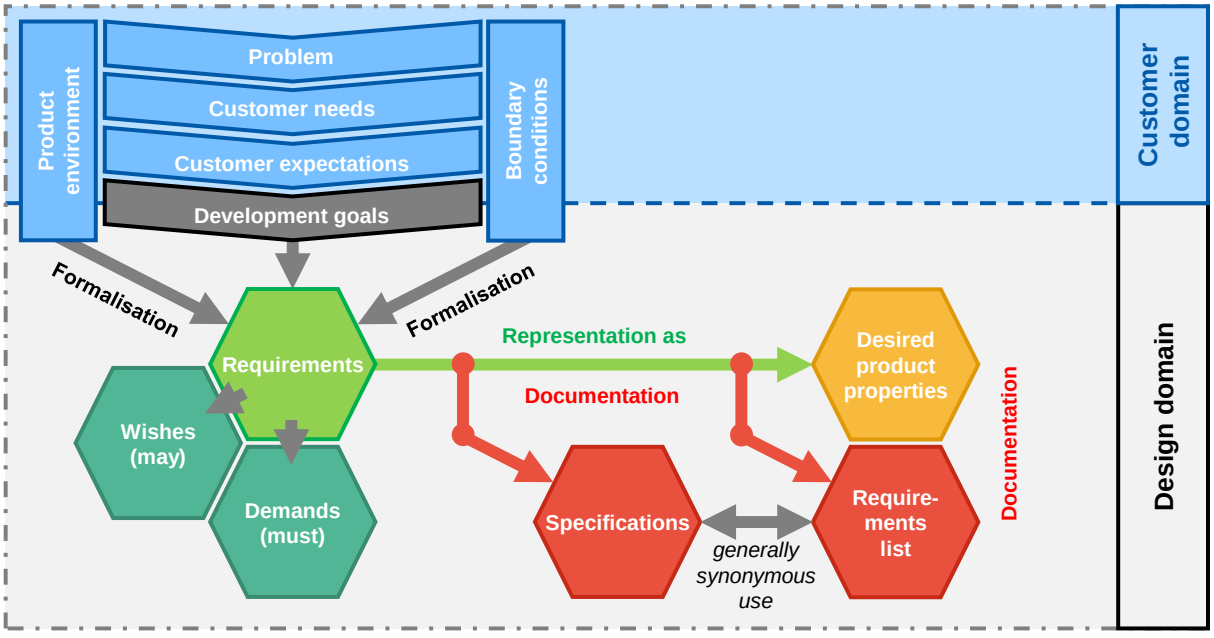

Figure 3. Conceptually differentiated requirement terminology

Customer needs result from a perceived **problem** or undesirable situation (Cascini et al., 2013). This situation can be perceived by any stakeholder during any process in the envisaged product life cycle. This leads to **customer needs** that are mostly implicit or hidden and cannot be explicitly expressed by customers (Ericson et al., 2009). They arise due to an implicitly or explicitly perceived problem by the customer.
The predominant customer need underlies the representation of **customer expectations** of a technical product. Customers have specific suggestions for the technical product, which are included in the concept of customer expectations. Therefore, the causal chain is illustrated in the customer domain, starting from an undesirable situation as a perceived problem, resulting in customer needs that are directly represented as customer expectations.
In the translation of customer needs and expectations into the language of product designers, **development goals** form a major specification step. They form the base of the design domain for the

formalisation of information from the customer domain. Customer expectations are mapped onto development goals, which provide information for pursuing the development process. The development goals include customer expectations of the technical product and are thus predicated on customer needs. Therefore, development goals implicitly represent anticipated customer needs (Eder and Hosnedl, 2008). In addition to the customer perspective, external conditions have to be considered, e.g. envisaged operating conditions resulting from the **product environment**, and compliance with legal regulations and normative guidelines, which are considered as **boundary conditions** during the development of technical products.

Compared to requirements, customer expectations are relatively vague in their validity for product designers. **Requirements** result from the envisaged product environment, development goals and boundary conditions. Conceptual distinction between requirements and desired product properties is essential, since most conceptual requirement definitions imply content agreement. As a result of this implied agreement, relevant customer needs could be overlooked or misinterpreted during the development process. Inadequate product function could result. These misinterpretations mean that the product purpose is not fulfilled, leading to customer dissatisfaction during use.

Therefore, requirements represent **desired product properties** that are determined during the course of the development process, according to defined and formalised requirements. Product properties are documented separately to characteristics and their values (Lindemann, 2009). Their values may be qualitative, quantitative or comparative (Gramlich, 2013). Contrary to requirements, the desired product properties do not have a specific prioritisation, as they represent the target system of the technical product that is to be developed. Since requirements form the fundamental base for every decision made in the development process, they are prioritised into demands and wishes. **Demands** must be fulfilled, thus ensuring the acceptance of a developed potential variant in the selection process (Pahl et al., 2007). **Wishes** can be realised, but not necessarily. They increase the evaluated quality of the technical solution in the evaluation process but do not contribute to the rejection of a potential variant in the selection process.

The **requirements list** is a commonly used documented form of requirements. It represents a specific formalised documentation of requirements. **Specifications** are often used synonymously to the requirements list and refer to the documented presentation of requirements (Sudin and Ahmed-Kristensen, 2011). Therefore, using the term requirements list for the documented form of requirements is beneficial as it avoids confusion with continuously revised and specified requirements.

3.2 Terminological clarification of requirements

As analysed in previous sections, requirements form the initial and fundamental base of every development process. To ensure that customers are content with the technical product developed, the desired product properties have always to align with the underlying requirements. The differentiated conceptual understanding enables better methodological support of the requirement acquisition process. Therefore, three types of requirements need to be distinguished (Figure 4).

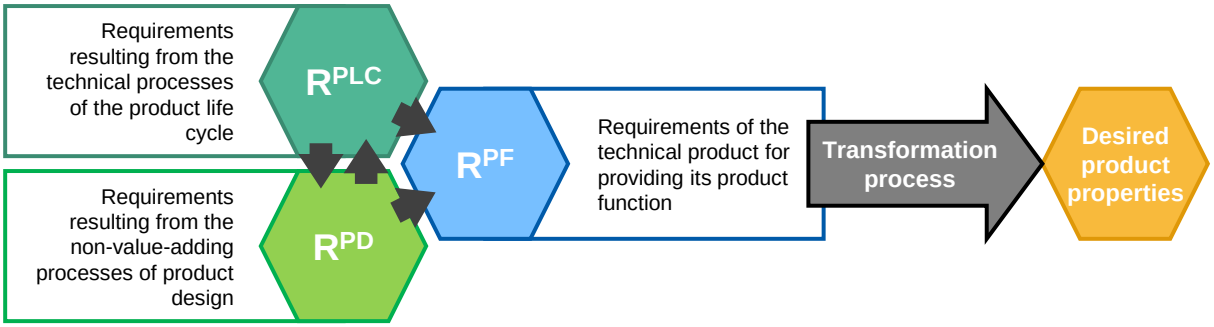

Figure 4. Types of requirements in the requirement space

The technical product is the focus since it fulfils the requested purpose by its function (Gramlich, 2013). **Requirements of the technical product for providing its product function (R^{PF})** directly refer to the technical product that is to be developed. They may be directly related to the property-based description of the technical product, according to the specification level. R^{PF} lead to qualitative, quantitative or comparative desired product properties of the technical product that has to be developed within its functional context.

As technical products pass many processes during their product life, more than just the requirements of the technical product (here the R^{PF}) need to be considered: Every phase in the product life cycle has to be considered.

Requirements resulting from the technical processes of the product life cycle (R^{PLC}) consider every aspect from the process perspective. Therefore, requirements result from each envisaged process of the product life cycle process chain that the technical product passes through in its product life cycle based on its particular role as either the operand or the operator, like material processing, production, product use and recycling/disposal (Abele et al., 2005). R^{PLC} also include process-overreaching demands and objectives, specifying the intended purpose of the technical product. R^{PLC} cannot be directly considered during the concretisation of technical products. They have to be transferred into requirements of the technical product.

Finally, **requirements resulting from the non-value-adding processes of product design (R^{PD})** incorporate boundary conditions that refer to the technical product using normative regulations, cost restrictions, limited personnel resources, etc. They are non-technical objectives for the non-technical processes of product design. R^{PD} result from all processes of the product development and product life cycle process chain. Examples of the aforementioned requirement types are shown for the development of a simple technical product (a wooden balance bike for children), which is described and modelled according to its product properties.

4 INFLUENCING CUSTOMER SATISFACTION BY DETERMINING PRODUCT PROPERTIES ACCORDING TO THREE TYPES OF REQUIREMENTS

Product properties are used for modelling and describing technical products. Customers usually evaluate the quality of technical products according to the perceived dependent product properties. These product properties cannot be influenced by product designers. Only independent product properties (Birkhofer and Wäldele, 2008) can be influenced and directly determined by product designers (Birkhofer, 1980). Formally-written, product properties are composed of a characteristic and a value (Lindemann, 2009). Out of necessity, product properties are determined during the entire product development process according to the documented requirements (Eder and Hosnedl, 2008). According to the actual concretisation process, product designers have to determine product properties of the technical product in a way that best fits the acquired requirements. Only when product designers interpret customer needs correctly does the developed wooden balance bike (Figure 5) have the appropriate product properties to make the stakeholder (in this case the children) content and happy during use.

Figure 5. Product properties using the example of a wooden balance bike (picture credits by Lloyds Worcester Ltd, 2014)

It is challenging for product designers to determine the appropriate independent product properties of the wooden balance bike according to the formulated requirements and customer expectations. Customers may expect that the wooden balance bike is robust, does not hurt the user, can be purchased inexpensively, ensures a comfortable ride and provides a lot of riding enjoyment. Above all, children should be content with their first experiences of the wooden balance bike to support the learning process of finding their feet and thus improving the sensibility of stability.

Wooden balance bikes provide a seat on which toddlers may sit and move the wooden balance bike using the repulsive force of their feet. For example, the specific bore diameter for the appropriate assembly of bearings represents a *requirement of the technical product for providing its product function (R^{PF})*, since the repulsive force has to be transferred to the ground to cause a forward movement of the wooden balance bike.

Customers may demand a simple design that should make wooden balance bikes robust and easy to use. Every edge is chamfered or rounded to guarantee that no child is hurt during use of the wooden balance bike. Since toddlers vary in size, the wooden balance bike's saddle should be adjustable. The padded saddle provides comfort during use. Wood from sustainable sources fulfils ecological sustainability criteria and meets the customer need to buy ecologically sustainable products. All of these desired product properties are transformed from *requirements resulting from technical processes of the product life cycle (R^{PLC})*, focussing in this case on the production and use of the wooden balance bike. Due to the need for children to have fun during use of the wooden balance bike, the injury risk on sharp edges must be minimized. This necessitates a requirement of the production processes that every edge must be rounded during production.
Finally, the wooden balance bike may have restricted development costs, since it should be affordable. These boundary conditions are considered during the development of the wooden balance bike as *requirements resulting from the non-value-adding processes of product design (R^{PD}).*

5 CONCLUSIONS

This paper presents the results of a systematic literature analysis. A lack of conceptual clarity in the huge field of requirements results in a confusion of content-related terms. According to the purpose of requirements in development processes, the conceptual definitions mainly fit into five major categories. The classification is not strict, since the conceptual definitions partly fit into one or more categories. The systematic literature analysis of conceptual requirement definitions provides a valuable base from which the essential requirement terminology is clarified.
The causal dependency of *problems, customer needs, customer expectations, development goals, requirements, desired product properties, specifications* and the *requirements list* is differentiated, leading to the distinction of three requirement types (R^{PF}, R^{PLC} and R^{PD}), which provide a differentiated conceptual understanding of requirements. This distinction opens up the potential for better requirement acquisition with methodological support during the product development process.
Furthermore, the proposed differentiated conceptual understanding supports product designers in the systematic transformation of requirements into desired product properties. Thus, product designers are able to skilfully determine the relevant product properties that have maximum agreement with the underlying requirements and make a significant contribution to having content customers, since product designers can more easily interpret customer needs and consider them more efficiently during the development process.

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