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A NECESSITY-BASED METHOD FOR PRODUCT REQUIREMENT ELICITATION AND CLASSIFICATION

Summary

A new necessity-based method for the elicitation and classification of requirements in the early phases of the product design process is presented. The purpose is to guide a design engineer through the process of requirement elicitation so as to compile a more appropriate requirement list and avoid under- and over-constraining a product.

The new method is based on the extended Form, Fit and Function approach. Its steps are derived from an in-depth analysis of literature sources. The applicability of the method is shown on a case study on residential solar panels. The method is validated by a case study on an air ventilation register box and by expert opinion.

The necessity-based method fills the gap in the well-established methods for requirement elicitation and classification. It gives an insight into which requirements are important for certain product. The elicitation part of the new method reminds a design engineer of important case-related requirements. The classification part helps establishing rules on mandatory requirements.

Key words: *design methodology, design process, design theory and methodology, product design*

1. Introduction

Definition of a necessary requirement

There are many ways in which a need for a requirement could be determined. Additionally, each product has an infinite number of possible requirements and sorting this infinite number of requirements based on necessity is a great challenge. In this paper, a necessary requirement is defined as a requirement that must be defined in the requirement list (RL). If this is not the case, an additional iteration of the design process occurs with the purpose of defining the missing necessary requirement. This additional iteration causes extra costs and results in longer time-to-market. Booker [1] found that such iterations take about 30 % of the whole product development time, which consequently means significant reductions in gross profits. In addition, it has been found that 80 % of requirement changes originate from design process causes and only 15 % of them are caused by customers [2]. Hence, a necessary requirement in the context of this paper is a requirement which should be defined in the earliest phases of the product design – on the one hand, it does not over-constrain the product, and on the other hand, its absence from the RL causes additional costs and work to the company.

Problems with requirement elicitation

Requirements are involved in every step of the product design process. The motive for developing a new product is usually the need or needs of a customer. These needs are expressed in the form of requirements. After the initial recognition design engineers use requirements as a frame by which product's features and properties are constrained. At the end of the design process initial requirements serve as benchmark to which the newly developed product is compared. The requirements, elicited during the early phases, are gathered and documented in the so called requirement list (RL). It is natural for some requirements (for example, some system requirements) to be defined at the very outset of the product design process. The customer requirements that initiate the process of product design are also known in this early phase [3].

However, not all requirements can be defined in such a straightforward manner. There are two important issues relating to defining the initial requirements: the under- and the over-constraining of the product. Under-constraining means not identifying and determining all the necessary requirements that are essential for the next phases of the product design. Chong et al. [4] name this problem over-framing and it is recognized and discussed also in [5, 6]. It occurs because not all the requirements that are present are also obvious, or because some requirements are so obvious that they are frequently missed in the process.

Over-constraining the product is also a recognized problem. Chong et al. [4] refer to it as under-framing and it means that a design engineer defines so many requirements at the outset of the process that there is little room left for alternative designs and solutions at later phases. This either leads to a sub-optimal design, or it suggests that the whole design process has already taken place, only informally and unsystematically [5]. Over-constraining the product in the early phases is a sign of the so called fixation on initial idea, which was observed and studied by researchers from different fields, for instance [7] for mechanical design, [8] for electronic engineering and [9] for architecture.

The reason for under- and over-constraining is often lack of experience of the design engineer. Designer novices may misinterpret signs and therefore may direct the design process into a sub-optimal direction [10]. A design engineer should pay attention to very different aspects of the product in different phases of its life-cycle. A typical example is designing and pricing a product simultaneously [11]. If the product design problem is ill-structured in early phases, this causes difficulties to less experienced engineers [12]. Hence, novices find it more difficult to obtain enough relevant information in the early steps of the process than their senior colleagues [13]. Nevertheless, the described problems can also be encountered by experienced design engineers. Although in the paper we state that the target group of the proposed method are novices, the systematic approach with clear guidance can also be a significant contribution to the work of more experienced engineers, who sometimes need a deeper insight into their product and its requirements (for instance to avoid fixation).

Literature offers some answers about under- and over-constraining. In [14], a hierarchical structure of the decision-making process is proposed, but no concrete methodology for tackling the problem is suggested. A transformation of a “real world” design knowledge representation into a structured Design Space Framework has been discussed in [4]. This model should be more applicable for further use. Some propositions have been made in the form of intelligent decision support for narrower fields, such as computer-aided design [15]. In requirements engineering (new software design) the use of the concept of personas is suggested [16, 17], but the application of this method in context of mechanical product design would be rather complex. Another method, suggested by software engineering authors, is Experiential Expression [18] but there is again the question of application to mechanical design. Therefore, an approach towards avoiding over- and under-constraining a new mechanical product is lacking in the literature.

Nevertheless, methods of effective requirement elicitation can be found in the literature. Requirements need to be elicited and negotiated at the product development outset [19] and special care needs to be taken to avoid or at least successfully resolve all the emerging conflicts [20]. Azadegan et al. [21] propose a systematic elicitation process, similar to requirement elicitation workshops and in [22] a system for automated requirement elicitation is proposed, both propositions from the software engineering point of view. Some guidance on choosing the requirements is given to design engineers in the form of sample checklists of topics that could be part of a RL for the new product, for example [5,7].

Some interesting classifications of requirements have been published. A classification according to product lifecycle phases is a part of the EIA-632 (1999) standard, intended for the design of greater systems [23]. It also includes the functional classification of requirements. A bare classification of requirements by product lifecycle phases was also adopted in [24]. The Kano diagram [25] classifies customer requirements into expecters, spoken requirements, unspoken requirements, and exciters. Dieter and Schmidt [3] divide requirements on the basis of the extent of design engineer's options. Requirements are hierarchically classified into stakeholder requirements, system requirements, subsystem requirements and component requirements in [26]. Another hierarchical approach that could be undertaken prioritizes (already established) requirements using the first house of the Quality Deployment Function (QFD), i.e. "the house of quality" [27]. The QFD also suggests some ways of eliciting requirements, for instance via interviews, surveys, etc. There also exist hierarchical structures of requirements, reused in the design of a new product of a product family [28, 29].

It can be concluded that no effective answer to the question: "Is this requirement necessary for this product?" has been given yet. The examined classification methods mostly discuss the division of already elicited requirements and the elicitation methods do not focus on the content of the requirements. They hence offer guidance to the design engineer towards the elicitation of some requirements, regardless of their content, and after that guidance towards dividing them into groups with respect to different distinctions. But the question of relevance of the elicited and later classified requirements remains unanswered by the literature. That is why the main questions of our research were: "What are the necessary topics of requirements for this product?", "How to know whether or not a product is over- or under- constrained by the RL?", and above all "What is a systematic approach towards eliciting an appropriate RL?" As an answer to these questions we propose a method that groups requirements into necessary and optional requirements on the basis of a specific product definition.

In the next section, the definition of requirements that are necessary for all products will be tackled. Then, a method for narrowing requirements to the level of product-specific requirements will be presented. Optional requirements will also be defined. After that, the method for eliciting requirements according to necessity will be presented from the user's (design engineer's) point of view. To show the process in a more concrete manner, a case study on eliciting and classifying requirements for residential solar panels is presented. The method is validated by a case study on air ventilation register box design. The findings and possible future investigations are summarized in the Conclusion.

2. The new necessity-based method

2.1 Extended Form, Fit and Function approach

The Form, Fit and Function (FFF) is a well-established approach to assessing whether a new (different) part of a product affects the product as a whole or not. The concept was first introduced in 1970s within the U.S. Air Force for measuring acquisition and interchangeability of parts (it is well described, for instance, in [30, 31]. The part is typically a single component that is a piece of a greater mechanical system (product). The effect of the part on the system is assessed from the points of view of form, fit and function. By form we usually understand physical properties which uniquely determine certain part, such as shape, dimension, weight and others. Fit are the attributes of the part that represent its ability to be integrated physically into the mechanical system, for example, the distances between part's and system's surfaces. In the context of FFF the function is defined as the action or actions that the part must perform under certain conditions, mostly determined by the mechanical system.

According to such definition the FFF approach has been applied to the processes of component design, for example, in the arms industry [32, 33]. ElMaraghy et al. [34] presented the geometrical interpretation of FFF in the form of manufacturing tolerances. Baker [35] described different obsolescence mitigation methodologies where FFF was the criterion of interchangeability of elements.

We employ the FFF approach for a slightly different purpose. We redefine the form, fit and function concepts so that we can establish a basic definition of a product. With the word "product" we now refer to any engineering design result – a single component or a system of components. Product does not need to be a part of some greater system to be able to be used in eFFF (as opposed to FFF). Therefore, we are going to extend the current view of FFF and name this extended approach extended Form, Fit and Function or eFFF.

In order to divide possible requirements into necessary and optional requirements on the basis of a particular product, some product definition needs to be introduced. Such product definition has to be set as generally as possible so as to provide a basis for our method to be applied to a wide variety of designed products. We find that eFFF is a sufficiently universal and, on the other hand, an increasingly specific approach for defining products and hence it can be used as the basis of the proposed method.

We extend the form, fit and function concepts as follows:

- form: As in FFF, form is a collection of physical properties of the designed product. Since all geometrical properties belong to the group *form*, the properties that describe geometrical fitting with other components or greater systems also belong to this group (and not to *fit*, as one could assume). We take manufacturing process as a subset of *form*, because the manufacturing process has a direct impact on geometrical properties (e.g. shape, dimensions, surface roughness, etc), physical properties (e.g. conductivity, density, etc) and mechanical properties (e.g. stiffness, strength, fragility, etc), namely:
    - flow of materials: The subset includes properties of the initial part of material (blank) and its transformations into the final product. It could also be viewed as the flow of materials along the production line (more about flow of materials in [36]).
- fit: In the new concept we divide fit into
    - fit people: This class contains properties that describe the interaction of the designed product with humans, including ergonomic and aesthetic properties, as well as evaluations regarding the intensity of contact and possible dangers for humans when interacting with the product - examples of properties are shown in [37, 38].
    - fit environment: Fit environment is similar to fit people. The difference is that in this set of properties the ones regarding the interaction of the product with the environment are considered. Some further examples of properties are described in [39].
    - fit economy: Properties herein describe the relationship between the product and the general economy and economy related issues (examples in [40]).

- function: The reinstated definition of function is relatively close to the original one. Properties included define the operations or intended actions of the product. We divide this group as follows:
    - flow of energy: In many cases the expected function of a product is to transform energy from one form to another. The properties observed herein usually consist of the input and the output form of energy and the intermediate transformations (examples in [41]).
    - flow of information: Similarly to flow of energy, the group flow of information includes the properties of the input and the output form of signals or information and their intermediate transformations.

Both flows are mathematically described (with examples) in [42].

We now clarify some terms, referred to in the above definitions:

- components of the product: From the structural point of view it is recommended that some autonomous properties are attributed to more complex or independent components – this applies mainly to properties that have different values for a component than for the product.
- properties: The properties are elements of eFFF that may or may not be used as requirements for a specific product.
- product lifecycle: Many of the properties have different values in different product lifecycle phases. Therefore, for some properties it is essential to state which product lifecycle phase (LCP) they refer to in order to be useful as product requirements. More detail on product lifecycle can be found in [43].

An important advantage of the eFFF product definition is its simplicity. A design engineer needs to provide very basic information to define a property. The complex properties are broken into lowest level components (e.g. input, output). This simplifies the product definition and subsequently minimizes the possibility of requirement ambiguity.

In order for the method to be applicable, some concrete and unambiguous guidance should be given on which requirements actually belong to eFFF. As stated, in eFFF, there are no requirements but only properties, that is, items that can be used as requirements – depending on the designed product and design circumstances. eFFF is the universal part of the new method for RL elicitation. eFFF properties are requirements, most frequently mentioned in the literature or in RLs in practice. We decided to analyse literature to extract properties that are usually recommended for inclusion in a RL. Many sources [3, 5, 7, 10, 12, 24, 26, 27, 34, 36-42, 44-49] were used for this purpose. Notice that some of the used references are general guides for design engineers (e.g. [3]) and the others are specific problem-oriented papers (e.g. [48]). Such a divergence in the used literature was employed in order to obtain a general and a specific view. We studied the listed sources carefully and we extracted the most generally used requirements. We qualitatively unified requirements with identical content and assessed weights for each requirement citation. After that, the weighted numbers of requirement citations were summed and requirements with the greatest sums qualified for eFFF properties. eFFF properties were finally refined with the help of expert opinion. We then sorted the properties by the groups of the eFFF structure and got the results, presented in Table 1 (the first three columns). We call the eFFF properties that are chosen by the user Universally Necessary Requirements (UNRs).

Table 1 eFFF properties connected to PSNR topics

eFFF		PSNR topic / eFFF property	Geometry	Kinematics	Forces	Energy	Material	Signals	Safety	Ergonomics	Production	Quality control	Assembly	Transport	Operation	Maintenance	Recycling	Costs	Schedules
FORM	flow of materials	input material	★		★		★				★	★		★				★	★
		material transformations	★				★		★		★	★	★					★	★
		output material properties	★				★	★	★		★	★	★	★	★	★	★		★
		material flow rate (production rate)	★				★				★		★	★				★	★
	other properties	shape	★	★	★	★	★		★	★	★		★	★	★	★			
		fit with another component/product	★	★	★	★	★		★		★	★	★		★	★			
		dimensions	★	★	★	★	★			★	★		★	★	★	★	★	★	
FIT	fit people	type of contact with people	★	★	★	★	★	★	★	★					★	★			
		target group of users	★	★	★	★	★	★	★	★			★		★	★			
		probability of danger to people	★	★	★	★	★	★	★	★	★	★			★	★			
		potential/most likely/worst case scenario injuries	★	★	★	★	★		★	★	★	★	★		★	★			
	fit environment	natural resources at risk because of the product			★	★	★				★	★		★	★	★	★		
		potential quality and quantity reduction of the endangered sources			★	★	★		★		★	★		★	★	★	★		★
		(partial) recyclability of the product	★			★	★		★			★				★	★	★	
		disposal strategy	★			★	★		★			★	★	★		★	★	★	★
	fit economy	deadlines					★	★			★	★		★				★	
		product cost and price	★		★		★	★	★		★			★		★			
		sale rate					★				★	★						★	
		similar available/patented products	★			★	★	★		★		★			★	★	★	★	
FUNCTION	flow of energy	input energy	★	★	★	★	★		★	★					★	★		★	
		energy transformations	★	★	★	★	★		★				★		★	★			
		output energy	★	★	★	★	★		★	★			★		★	★			
		energy flow density	★	★	★	★	★		★				★		★				
	flow of information	input signals	★				★	★	★						★	★			
		signal transformations	★				★	★	★				★		★	★			
		output signals	★				★	★	★	★			★		★	★			
		signal flow rate	★				★	★	★				★		★				

2.2 Universally Necessary Requirements (UNRs)

As shown in the analysis in the previous subsection, some requirements are defined for almost all new products. It does not mean that for an appropriate RL all the eFFF properties should be defined – if this is the case, the product is most probably over-constrained. It only means that the eFFF properties that are defined belong to the group of UNRs. These eFFF properties inherently and intuitively form a starting point of the systematic design. It is obvious that without understanding of what will the function of the product be and without having at least a general idea about the dimensions of the product (e.g. will they be measured in millimeters or kilometers) and without knowing whether or not people will be in contact with it, there is no point in progressing to the next stage of the design process (usually concept generation). And that is why it is reasonable to expect that at least some of the eFFF properties are defined in the early phases of the product design process (i.e. before the RL).

It is important to note that a product may consist of several fairly independent and/or complex components. Each of these components undergoes some changes through the product LCPs. Therefore, the values for the same eFFF property can be different for different components and even for the same component in different LCPs. When defining an UNR it is hence essential to indicate for each component in which LCP the value is valid. Clearly, UNRs can also be defined for the product as a whole. It is also necessary to check the applicability and relevance of each eFFF property, given in Table 1 for each component (including the product as a whole) and for each LCP (but as stated, not all eFFF properties should be defined as UNRs). That is the only way we can make sure that no necessary requirement from this group is missed in the process.

The UNRs indicate which elements of the new product are specifically important, at least from the design engineer's perspective. They build the core of the following steps of this necessity-based requirement elicitation method.

2.3 Product-specific necessary requirement topics

In the previous section, the UNRs have been established on the basis of eFFF. Now, there remains the question: "Which requirements are necessary for the specific product being designed?" The new necessity-based method answers the question with the help of the UNRs. Each eFFF property (and hence the UNR) can be connected with certain topics of requirements. Because these topics lead to the recognition of product-specific necessary requirements (PSNR), we call them PSNR topics. In the method which is proposed, PSNR topics are the headings of Pahl and Beitz's checklist [5]. The connections between the eFFF properties and the topics can be recognized intuitively or through experience. When we search for connections, we inherently ask ourselves the following questions: Does the eFFF property affect the PSNR topic directly? Does the PSNR topic affect the eFFF property directly? For example, it is obvious that the eFFF property Input Signals is closely related to the PSNR topics of Geometry, Material, Signals, Safety, Operation and Maintenance, but the connection between Input Signals and Recycling is not so obvious. In addition to the eFFF properties, LCPs can also be linked to specific PSNR topics in a similar manner. All the connections between the eFFF properties and the PSNR topics are shown in Table 1 (cells of the matrix containing a star symbol refer to a connection and white cells show that there is no direct connection). It can be seen that the PSNR topic of Material is connected to every eFFF property, which means that some implications about it need to be stated in the RL in any case. For other connections it can be said that the eFFF properties from the same eFFF branch are connected to similar topics.

Table 1 has been constructed on the basis of the connections, encountered in the literature and on the basis of expert opinion (experts from different fields of industry were interviewed). The appropriateness of the presented connections was validated by the PSNR calculations for different products and by a later comparison of the calculated PSNR topics with the topics provided in real industrial RLs. It can be shown that Table 1 holds for very different products. The appropriateness of the positions of the stars was confirmed by an extensive analysis of industrial RLs, RLs found in literature and the resulting products (for the sake of brevity the details of the analysis are not presented in this paper). Hence, the shown connections are in the correct places for a wide variety of different products. Yet, if the method is to be used for an exactly known type of products (for example, a family of products or for variations of the same product), the stars in Table 1 can be optimized for that type. We expect most of the stars to stay as they are, though some of them might move in accordance with a specific product type. But, as stated, the presented connections are validated and valid for a broad range of different products and product types in general.

For the establishment of PSNR not all the topics, linked to UNRs, should necessarily be investigated further. It follows from Subsection 2.1 that the model of product requirements is built of components in different LCPs. Each component-LCP couple, as well as each LCP on its own, is connected to its PSNR topics. The described requirements model is shown in Fig. 1. In order to judge which topic is most likely an important topic of PSNR and thus worth investigating further, we group the PSNR topics by components and LCPs.

The weight of each eFFF property-PSNR topic connection is a reciprocal of the number of PSNR topics, connected to the observed eFFF property. The reciprocals are weighted by PSNR topics, so that the sum of weights for all eFFF properties for every topic equals 1. Say i is the eFFF property index, j is the PSNR topic index, $x_{ij} = 1$ when the Table 1 field for the connection contains a star and $x_{ij} = 0$ when it is empty. Then the weight of the connection w_{IJ} is given by Equation (1):

$$w_{IJ} = \frac{\dfrac{1}{\sum_{\substack{j=1 \\ i=I}}^{17} x_{ij}}}{\sum_{\substack{j=1 \\ i=J}}^{28} \dfrac{1}{\sum_{\substack{j=1 \\ i=I}}^{17} x_{ij}}} \tag{1}$$

The weights are summed (only for the defined UNRs) for every topic. In that way one gets the importance of every PSNR topic. The main assumption, validated by the method testing, is: **Topics with highest sums are important for the product and there exists a high probability that some requirements in relation to the content that belongs to the topic should be defined.**

Grouping can take place, as described, at the lowest level (for each component-LCP couple), however, if a component-LCP couple only has for instance one UNR defined, then there is a possibility of grouping at a higher level, i.e. grouping by a LCP or by a component. This enables the user to concentrate on the PSNR topics, most relevant for the designed product and prevents him from losing the focus on possibly immaterial topics. It should be noted that the judgment on which PSNR topics to choose for further investigation is somewhat subjective. Some users would take into account, for instance, the three topics with larger sums or all the topics with the sum greater than 0.8, or all the topics with the sum greater than 0.75 times the maximum topic sum, or use some other evaluation approach. It can also happen that many topics have the same sums or that some irrelevant topics appear with rather large sums – in such cases some logical decision has to be made on which topic to choose. If the proposed method is integrated into a decision support system, this could be of help to the users that find this subjective part difficult to tackle (usually because of the lack of experience).

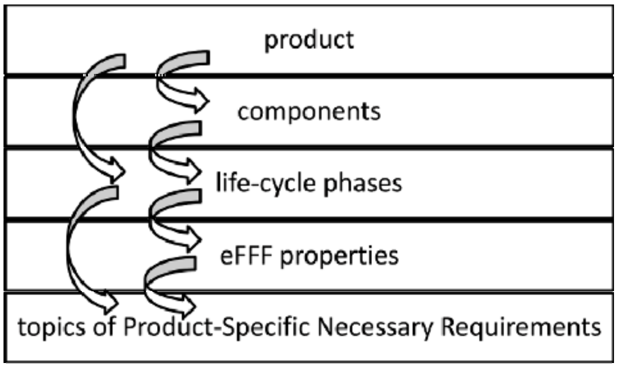

Fig. 1 Product requirement elicitation model

2.4 Product-specific necessary requirements (PSNRs)

Once the relevant PSNR topics are selected, some requirements with the related content should be defined. It is fairly obvious, which requirements belong to which PSNR topic. For example, it is straightforward that a requirement regarding product disposal is part of the Recycling PSNR topic. But, there are two issues arising from the observation of the distribution of requirements by PSNR topics.

Firstly, there are some requirements that belong to more than one PSNR topic. Such requirements should methodologically be included in all the related topics because the chosen PSNR topic must include the requirements that could potentially be important for the product. For example, toxicity of a material belongs to the topics Material and Safety and it should be included in both of them to remind the user that it might be necessary for the newly designed product that a requirement on toxicity is defined.

Another issue is that in order for the method to be useful in practice, the most probable requirements for each PSNR topic should be gathered. In that way the user can select a PSNR topic and then go through the gathered requirements to see whether or not any of them is applicable to his or her case. The risk exists that some important requirements are lost or missed in the process of gathering. If such a lost requirement is then not listed within the related PSNR topic, this could mislead the user into thinking that the requirement is not important or it could simply lead the user to forgetting to define the requirement. This means that the list of PSNRs, created for each PSNR topic, is informative, inherently incomplete (due to the infinite number of possible requirements related to each topic) and hence, non-exhaustive. We therefore wrap up the step of eliciting PSNRs with another checklist, or, more accurately, with a set of checklists – one for each PSNR topic.

The requirements of each checklist are gathered from different sources and should be updated with new sources and experience. The first suggestion of useful checklists is prepared and shown in Table 2 (only for topics Geometry, Assembly and Material for the sake of clarity and brevity). The checklist requirements were gathered in a manner similar to the one carried out when obtaining the eFFF properties. Literature sources [3, 5, 7, 10, 12, 24, 26, 28, 34, 36-42, 44-49] were analyzed again, and most of the encountered requirements were extracted. They were distributed according to the PSNR topics they are related to and there was no further refining. Some requirements were added according to the advice of expert (senior) design engineers.

Table 2 PSNRs corresponding to PSNR topics (partial)

PSNR topic	possible PSNRs
Geometry	arrangement, surface treatment, connecting elements, number of components, sizes and shapes of components with regard to each other, space requirement, standard elements, size, height, breadth, length, diameter, tolerances, clearance, possible dimensions according to preferred material, product's (component's) own weight, standards, laws and patents
Assembly	installation, siting, foundation, changeability, possible component breaking during installation, standards, laws and patents
Material	preferred material, compatible materials, material properties, lubrication, component's own weight, physical and chemical properties, auxiliary materials, prescribed materials, possibilities of production transformations according to the production rate, procurement possibilities, recyclability, danger to environment, waste of limited natural resources, standards, laws and patents

After the step of determining UNRs has been completed, a design engineer needs to define also the requirements that are less general and more specific to the product that he/ she is designing. These requirements are necessary, because they usually give a lot of information about the specific situation of the product production. If the main constraint is, for instance, the manufacturing factory, then some requirements will surely be elicited that give information about capabilities and possibilities of the factory in relation to the product. That is why such characteristics are denoted as PSNRs.

2.5 Optional requirements

Besides the UNRs and PSNRs, there exists another class of requirements in the proposed necessity-based requirement elicitation and classification method. These are the requirements that are not as general so as to belong to the eFFF properties and they also do not belong to the PSNR topics, chosen on the basis of the UNRs. They are usually explicitly stated by the stakeholders and are very important. Because they indeed need to be included in the RL, they are classified as optional requirements (OR).

When the process of defining the UNRs and the PSNRs is over, the design engineer check whether some other requirements, which do not belong to these groups, were elicited in the process. Such requirements could be some special features of the product, some innovations that distinguish the product from similar ones. Or they represent some other specialties regarding the specific product design.

3. Applicability of the new necessity-based method and under-/over-constraining controls

In the introduction, the traps and possible issues in the process of requirement elicitation are discussed. It is stated that the under- and the over-constraining of the product have been recognized and are serious problems. The proposed new necessity-based method aims at overcoming these problems by helping design engineers not to miss important requirements. It can be concluded that the engineers with greatest difficulties in this early step of the product design process are design engineers with lack of experience. This means that they are either inexperienced in general (mostly young design engineers who have just finished their formal education) or that the area of product design they are dealing with is new to them (for example, experienced design engineers who changed from designing one type of product to a completely different type, when changing a company or a department). The purpose of the method is therefore to guide a design engineer through the requirement elicitation process in a systematic manner that enables generation of a more appropriate RL.

For a design engineer the first step of this guidance, i.e. the first step of the new method, is to elicit UNRs. This is done so that the user works through the eFFF properties (described in Subsection 2.1 and Table 1) for each component and each LCP. The user first checks whether or not the eFFF property is relevant for a certain component in certain LCP. If it is not, he/she checks the next property and repeats the procedure until he/she reaches a relevant one. Every relevant property is defined by the user as an UNR.

Then the corresponding PSNR topics need to be found for each UNR (Table 1). The weights of identical PSNR topics that appear for a component and/or the same LCP (depending on the chosen level of grouping) must be added up. The PSNR topics with the highest sums of weights for the observed couple component-LCP or for the observed component or for the observed LCP need to be further investigated. Some judgment is required within this step.

In the next step, the recognized relevant PSNR topics are investigated with the help of (the full version of) Table 2. This means that the user checks through the PSNRs that belong to the PSNR topics, especially in respect to the observed component and the LCP (he/she can indeed be reminded of an important requirement for another component/LCP with the help of Table 2, which is positive). Some PSNRs are elicited from each topic.

The requirements that are explicitly stated in the early phases of the product design process (usually by stakeholders or by the design engineer himself) and which belong neither to the UNRs nor to the PSNRs also need to be written down. These are the ORs.

The last step is to write down a formally edited RL. It is a usual way to group all the elicited requirements by components and/or LCPs.

The method for requirement elicitation and classification based on necessity (and its background) is clearly shown in Fig. 2.

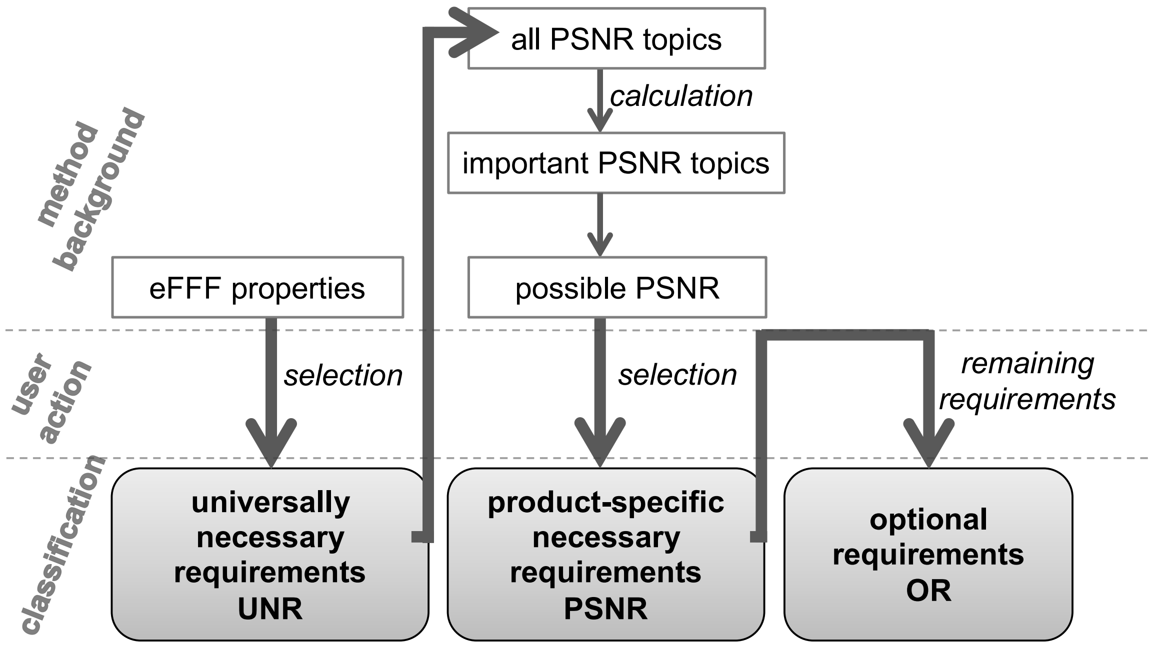

Fig. 2 Method for requirement elicitation and classification based on necessity

As stated, the requirements tend to change also in the later phases of the product design process. In case of changes, the use of the proposed new necessity-based method would be as follows:

- If the defined requirements stay unchanged and only their values are varied, then the method does not need to be used again.
- If the selected UNRs are different from the PSNR topics, they can be recalculated and the design engineer can find whether some new topics could be relevant for his or her product.
- If the PSNRs or the ORs are altered (added or removed) the RL should be re-checked for under- and over-constraining.

Therefore, the proposed method is also useful in the later phases of the product design process, especially when initial requirements for the product are re-discussed.

4. Under- and over-constraining the product

When the necessity-based method is incorporated in a decision support system, the controls for under- and over-constraining the product can also be implemented. In this case the user would be informed about under-constraining when:

- any of the Form, Fit or Function parts of eFFF is left with no requirements defined
- any of the calculated important PSNR topics is left with no requirements defined or
- a very small number of requirements is defined for the whole RL.

The user would be informed about over-constraining when:

- most of eFFF properties are defined as UNRs or
- a very large number of requirements is defined for the whole RL.

In this context, limits to "very small number" and "very large number" are set with respect to the usual number of requirements, defined in the industrial RLs that we studied. Mostly, the number of all requirements is around 10. "Very small number" is thus significantly smaller than 10 and "very large number" is significantly larger than 10. However, these limits should be adjusted according to the usual number of defined requirements for the specific industry branch (this number can vary from branch to branch).

Although under- and over-constraining controls are not an inherent part of the method for the necessity-based requirement elicitation, the proposed method offers the mechanism for measuring and testing under- and over-constraining. The method is systematic, which means that at each stage of the process (UNR, PSNR, OR), we the defined requirements can be counted and the appropriateness with respect to product constraining can be evaluated. Also, with the use of the method the existing real industrial RLs can be analysed and proper limits of under- and over-constraining that can be used for new RLs can be deduced.

5. Case study and an illustrative example of practical application: residential solar panels

5.1 The problem

The practical application of the proposed method is shown on an example of residential solar panels. The case study is based on the article of Chen et al. [50] in which the authors analyze customer preferences when buying solar panels. They compare the results of the revealed preference method with the results of a stated preference self-explicated survey. The revealed preference method was conducted using real market data from the California Solar Initiative database and the stated preference survey was conducted by using an internet survey of solar panel installers. The authors were not interested in which features and properties of solar panels are important for their design. Instead, they were examining which features and properties were important to consumers when deciding to buy specific solar panels.

The results of the self-explicated survey show which features the consumers will inquire about when buying solar panels. We can hence use them, namely, the list of the most important consumer preferences to establish the spoken requirements for the design of solar panels in our illustrative case. The elicited requirements at the outset are therefore (top 5 attributes from the stated preference survey):

- Cost: Price per watt should be comparable with other photovoltaic panels currently in the market.
- Aesthetics: Shape and colours of the frame should stand out from competitive solar panels.
- Warranty: Warranty should be at least of length which is average on the market for competitive products.
- Efficiency: Efficiency at standard test conditions should be higher than the efficiency of other photovoltaic panels.

These are the spoken requirements, usually given to the design engineer by customer or marketing department. However, the study of Chen et al. [50] considers the product from the buyer's point of view. The revealed (or stated) preferences clearly suggest which features of the product seem to be important for the end buyer and, consequently, which features design engineers should pay special attention to. However, the authors do not (directly) study the attributes that are important for the design of a solar panel. In addition to the customer spoken requirements, usually there are some other constraints for the design of a product that originate from the manufacturing company, available sources, logistical means, company's time-frames, financial position and so on. In our case study these requirements (partly taken and adapted from the Attribute definition list in [50]) are the following:

- ISO 14001 and IEC 61215 standards must be met.
- Panel packaging must not contain cardboard.
- The greatest possible panel length, available for the manufacture of cells and frames on the existing machines is 2 metres.
- Time-to-market should be less than one year.
- The manufacturing factory capacities include machines for the production of aluminium structural elements.

The task of a design engineer is to elicit all the necessary requirements and construct an appropriate RL as soon as possible. Let us imagine that the design engineer in our illustrative case study is inexperienced in eliciting requirements and thus decides to use the proposed new necessity-based method for finding appropriate requirements.

5.2 UNRs

For establishing UNRs the design engineer first needs to consider whether or not the product consists of any relatively independent and important components. Because it can already be seen from the list of wishes that the frame is viewed somewhat separately, it can be said that the residential solar panel consists of cells and a frame. Therefore, the design engineer must work through the eFFF properties, gathered in Table 1, for the product as a whole, for the cells and for the frame (both components are shown on Fig. 3). It is most convenient if the LCPs are noted along with the UNR definition.

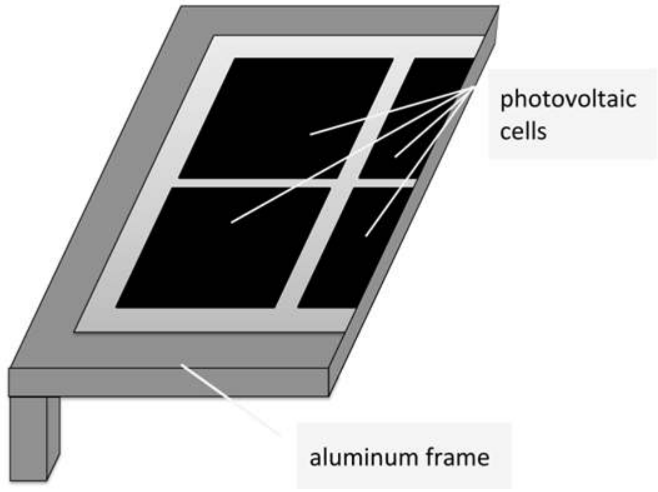

Fig. 3 Part of a photovoltaic panel and its components

According to the situation described in the previous subsection and according to Table 1, the design engineer defines the following UNRs:

For the product as a whole:

- Product price: price per watt is less than for competitive products (LCP = sales)
- Deadlines: warranty is longer than the average on the market (LCP = operation)
- Dimensions: full length of a panel is less than 2 metres (LCP = production)
- Deadlines: time-to-market is less than one year (LCP = design)
- Target group of users: general public – home owners (LCP = sales, operation)
- Type of contact with people: people will see the product (LCP = operation)

For the cells:

- Fit with another component: possibility of installing multiple cells into the frame, cables for carrying electric current (LCP = design, production)
- Input energy: sunlight – power, according to the location of installation (LCP = operation)
- Energy transformations: photovoltaic transformation of radiated sunlight into electricity (LCP = operation)
- Output energy: electricity – voltage according to the quantity of installed cells (LCP) operation)

For the frame:

- Shape: the shape of the frame should be different from the shape of the frames of competitive products (LCP = design, operation)
- Dimensions: the greatest length is less than 2 metres (LCP = production, operation)
- Input material: aluminium (LCP = production)

5.3 PSNRs

Having the UNRs defined, now it is time to choose PSNR topics for further investigation. The design engineer again studies Table 1, now also the right-hand columns, containing the topics of interest. Just looking closely at the LCPs for which the UNRs are defined, one can see that grouping by components will be most suitable, because the additional next-level grouping (by LCPs) would be pointless (mostly only a requirement or two would be defined for each group).

Six UNRs are defined for the product as a whole, four for the cells and three for the frame. The design engineer chooses to further investigate four highest sum topics for each component. As an example in Eq. (2), a calculation of the sum for the Cells component and the Assembly the PSNR topic is shown (the weights refer to the weights of the UNRs consecutively (as in Table 1), where the weight is 0 if the UNR and the PSNR topic are not connected):

$$\frac{\left(\frac{1}{11}+0+\frac{1}{9}+\frac{1}{10}\right)}{\left(\frac{1}{8}+\frac{1}{12}+\frac{1}{7}+\frac{1}{12}+\frac{1}{11}+\frac{1}{13}+\frac{1}{11}+\frac{1}{12}+\frac{1}{11}+\frac{1}{9}+\frac{1}{10}+\frac{1}{8}+\frac{1}{7}+\frac{1}{8}+\frac{1}{6}\right)}=\frac{0.3020}{1.6381}=0.1844 \qquad (2)$$

Having added up the weights of the PSNR topics the selected topics for the product as a whole are: Material, Signals, Production and Transport. For Cells the first eight topics have the same sum. The design engineer chooses the following for from the set: Material, Safety, Energy, Operation. For the Frame component the first five topics have the same sum. The following four are chosen: Material, Forces, Geometry and Production. From the full version of Table 2 the design engineer then defines the PSNRs according to the selected topics:

For the product as a whole:

- (Material) All the chosen materials should have a total weight that can be carried by the house roof.
- Material prices should result in a competitive total product price.
- (Signals) Sensors should be built into the system to prevent overheating and other dangers for people.
- (Production) Production of the whole product should be environmentally friendly and in accordance with the ISO 14001 standard.
- Quality of production should provide a warranty that is longer than the average warranty on the market.
- (Transport) Packaging should contain no cardboard.

For the cells:

- (Material) Chosen material should be in accordance with ISO 14001 standard.
- (Safety) Cell design should have the IEC 61215 certificate.
- Cells should be designed so that the possibility of overheating, fire, electrical shock hazard and similar is minimized.
- (Energy) Efficiency under standard test conditions should be higher than the efficiency of other photovoltaic panels.
- (Operation) Cell operation should fulfil warranty obligations.

For the Frame:

- (Material) Aluminium frame should be insulated so that it does not carry the electric current.
- (Forces) Frame should be strong enough to carry the weight of the cells and its own weight.

- Frame should be attached to the house roof and withstand different weather conditions (e.g. strong wind, storms).
- (Geometry) Design should be different from the design of the frames already on the market.
- Existing frame patents should be examined.
- (Production) In the production the existing machines should be used. Design of the frame must enable the exploitation.

Obviously, during the PSNR elicitation procedure the design engineer would be reminded of many other PSNRs, which is the very purpose of the exercise. These additional steps are not specifically described in the paper as we wish to show here the main idea of the new necessity-based method. Most of the new requirements that were not determined at the outset of the design process are elicited exactly in this step, when the design engineer tries to gather the requirements of which he/she is reminded.

5.4 ORs

There is a requirement that has not been involved in the UNRs or the PSNRs, but it was specifically mentioned at the outset of the project:

- Aesthetics: Colours of the frame should stand out from competitive solar panels.

This is an OR. During the PSNR elicitation procedure, which would encourage the design engineer to collaborate with the stakeholders, some additional (unexpected) requirements would probably arise. Some of them would then have to be classified as ORs.

5.5 RL and method discussion

The last step of the method is the creation of the requirement list. The requirements, stated as initiators of the process, as well as the ones elicited in the process (mostly while defining the PSNRs), now need to be grouped by topics (most conveniently by the PSNR topics or by the eFFF structure) and written in the form of a RL. Grouping at this stage is done purely to enhance legibility and transparency of the RL.

One can see from the described procedure that some requirements are spoken at the start of the design process and the others need yet to be elicited. The quality and quantity of requirements, initiating the process, determine whether or not a great number of new requirements will need to be elicited in the later steps of the necessity-based method. If the initially spoken requirements (by the stakeholders) are scarce and poorly defined, then some new requirements will need to be elicited already when defining the UNRs and many more will be determined during defining the PSNRs. However, if the initially spoken requirements cover most of the essential initial information and are given in some systematic way, then the number of the necessary newly elicited requirements will be smaller. In our study, the spoken requirements were already refined to a certain extent as the most frequently stated consumer preferences [50].

This on-going classification of requirements can be seen from the described method steps. During the progress of the method, the requirements are automatically classified as UNRs, PSNRs and ORs. This can be of significant practical help when designing new similar products or it can be a theoretical guideline when analyzing the design process.

One of the advantages of the necessity-based requirement elicitation method, which can be seen from the example, is the initiative to organize the requirements by components and

LCPs. That makes further phases of the product design process clearer to the design engineer as well as to any RL reader. Clarity can prevent mistakes and exposes difficulties if they appear [5, 14]. Another advantage is that the design engineer is constantly reminded of different aspects of the new product. He/she is urged to define form, fit and function of the product (eFFF), which leads to broadening the PSNR topics that are related to the defined UNRs. In that way the design engineer is reminded of the requirements that could easily have been missed. The new method is very systematic. That enables guidance of the design engineer from the initially stated requirements towards writing the RL in an orderly manner, which is positive, especially for less experienced users that are not sure which steps to take and at which point to take them. It is also worth mentioning that the method is ready to be implemented in the form of a decision support system, which would enable even more user-friendly guidance to design engineers through the process of requirement elicitation.

When examining the method closely, it can appear as rather time-consuming. The eFFF process, the PSNR topic choosing step and the PSNR determination need to be undertaken for all the components, which can mean quite a few iterations. If the user is unaware of the fact that only few requirements from each step need to be defined, the method could also mislead the user into over-constraining the product. On the other hand, the user needs to feel enough freedom to add some PSNRs to the corresponding PSNR topics. As stated, the checklists in Table 2 are only informative because the number of possible requirements is infinite and it can never be achieved that all possible PSNRs are listed. It also needs to be noted that the method is not deterministic – some degree of professional judgment is still present, mostly when choosing between the PSNR topics with the highest sums.

6. Case study and method verification and validation: Air ventilation register box

Our problem is the design of an air ventilation register box for offices, bars and private houses that connects the air-conditioner outlet channel to the ceiling diffuser (Fig. 4 shows the final product and all the requirements from the original industrial RL for the product are shown in Fig. 5). It is mounted inside a ceiling and made of galvanized steel sheet. In the original RL, obtained directly from the industry, some other requirements are also determined.

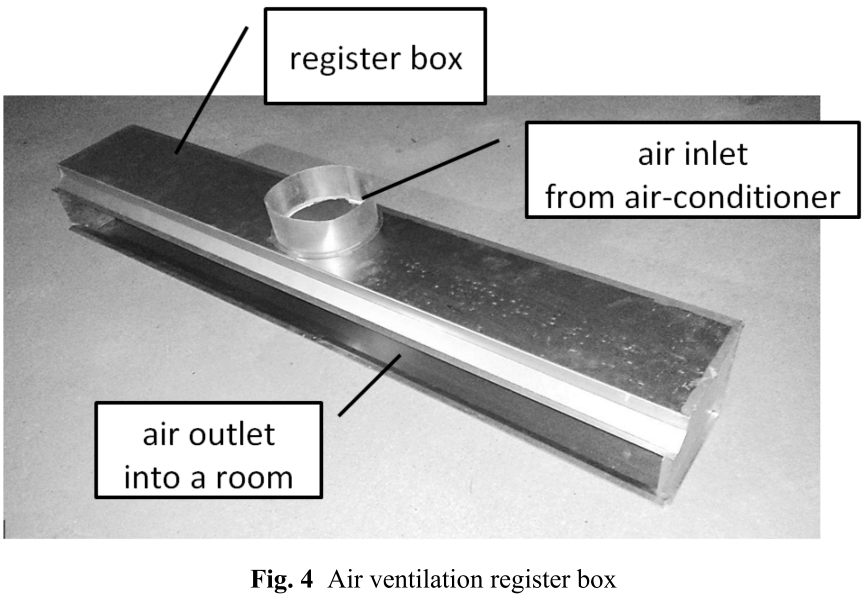

Fig. 4 Air ventilation register box

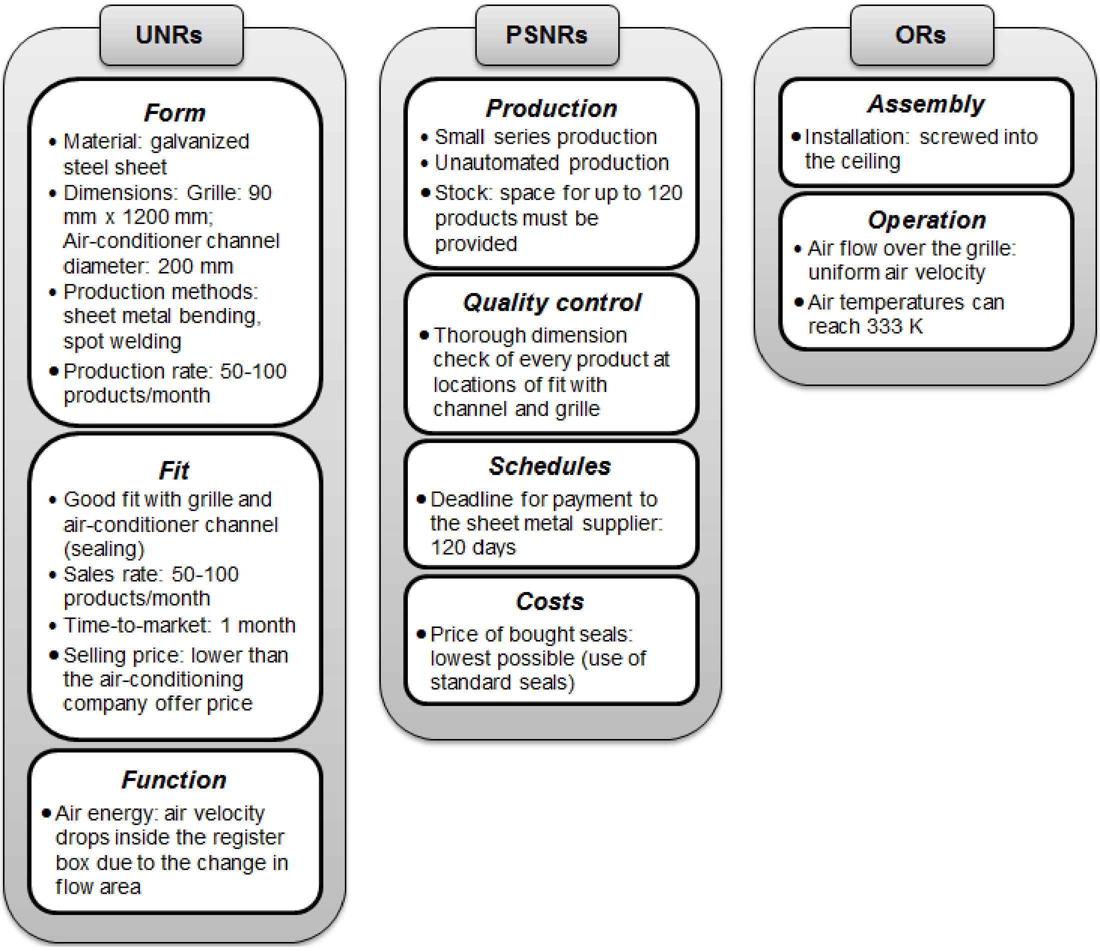

Fig. 5 The requirements of original register box RL classified according to the necessity-based method

6.1 Method validation on the basis of a real industrial case and expert opinion

To test whether or not the proposed necessity-based method truly leads the design engineer in the direction of creating a more appropriate RL, we compared the results of our method with a real industrial case and with expert opinion.

In the original RL four out of seven Form eFFF properties, three out of 13 Fit eFFF properties and one out of eight Function eFFF properties are defined (Fig. 5). The original RL hence fulfils the condition of at least one requirement from each part of eFFF being defined. This can be taken as a first sign of avoiding under-constraining. The above figures also tell that eight out of total 28 (29 %) eFFF properties are defined. From this fact it can be concluded that the product is not over-constrained until this point in the design process. The requirements that are not the eFFF properties but are defined in the original RL can be classified into the PSNR topics (the number of corresponding requirements is shown in brackets): Assembly (1), Production (3), Quality control (1), Schedules (1), Costs (1) and Operation (2). That shows good accordance with the calculated (Subsection 4.2) PSNR topics of the proposed method (weight of importance for the topic is given in brackets): Costs (0.73), Schedules (0.60), Quality control (0.53), Production (0.53) and Recycling (0.45). As can be seen, four topics coincide. That means that the method covers the topic selection process rather well. The requirements from the topics that differ are the ORs. The complete classification of requirements according to the proposed method is shown in Fig. 5. The defined requirements are also compared with the PSNRs, offered by the proposed method (examples are in Subsection 4.2). Three out of nine PSNRs and ORs are not offered by the proposed method, which means that these requirements should be included into the PSNR sets.

In general, the experts from the firm that designs and produces register boxes agreed that the method is a step towards increasing quality of RLs. They did notice that some more PSNRs could be offered. This would broaden the choice for RL authors and also remind design engineers of even more possible requirement options. However, there is some fear of over-constraining if the users of the method are not well informed that not all the offered requirements have to be defined. The experts feel that the method is not too time-consuming. These conclusions were obtained through interviews with experts.

6.2 Confirmation of positive contribution of the method

We were also interested in whether or not the method indeed simplifies and properly guides the requirement elicitation for novice design engineers.

The observed problem was the same as with expert design engineers. It was briefly described to 32 young design engineers (students of product design engineering), while the necessity-based method was not presented to them. They were then asked to answer some questions regarding the task of designing an air ventilation register box. First, they needed to choose which eFFF properties they would define. All eFFF properties are shown in Fig. 6, together with corresponding percentages of participants that evaluated them as important (light grey areas show the eFFF properties actually defined in the original industrial RL).

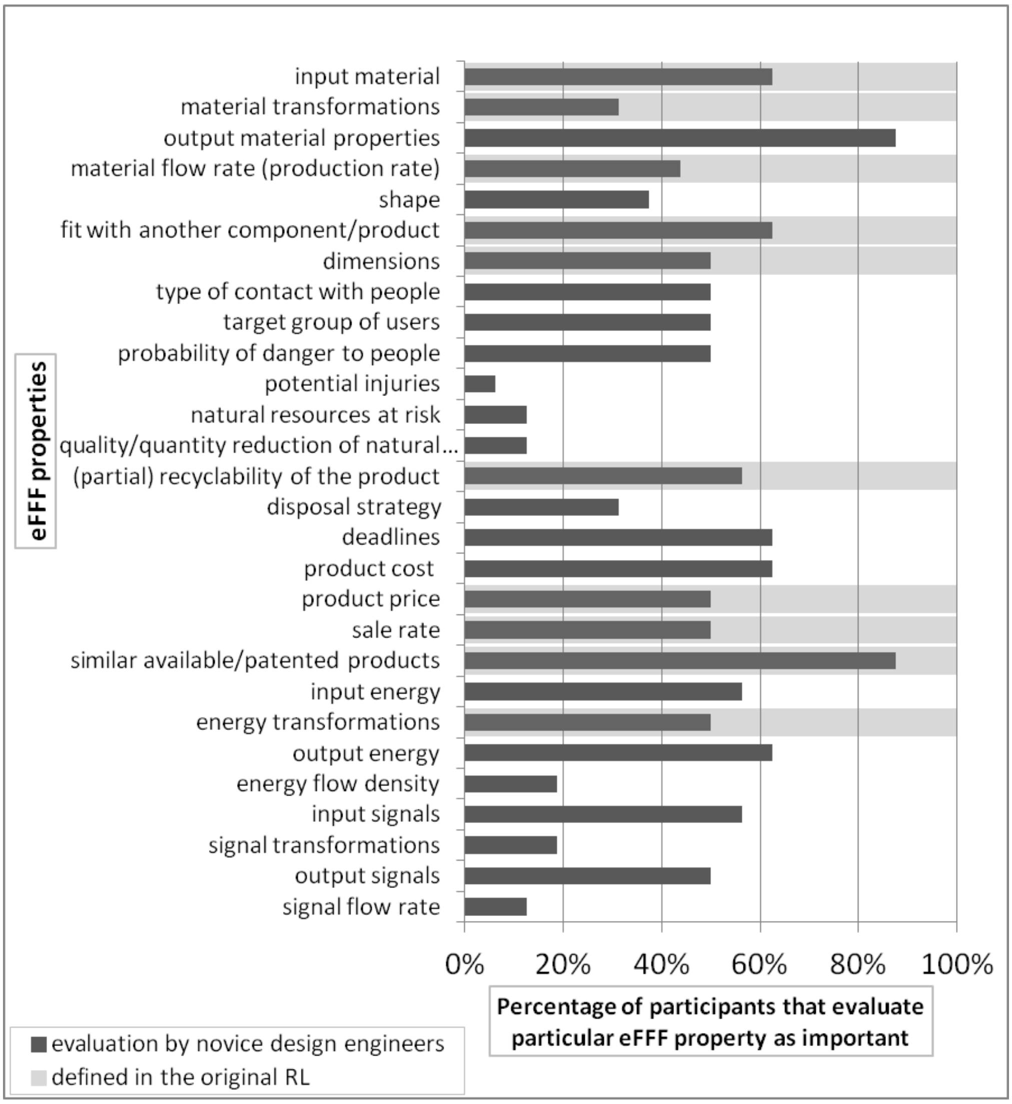

Fig. 6 eFFF properties evaluated as important by novice design engineers (percentages in dark grey) and properties actually defined in the original RL (light grey)

It turned out that one participant defined no property for the Function part of eFFF. When the method is implemented into a decision support system, this under-constraining issue can be avoided by suggesting to define a property for Function. Over-constraining showed to be a greater issue. 56 % of participants defined more than half of the eFFF properties, which could impose a problem in the later phases of the design process. Again, in a decision support environment, the user of the method could be alerted of the possible over-constraining. Fig. 6 also shows that the novice design engineers placed some emphasis on the Signal flow and Fit people eFFF properties, which is not the case with the original RL. This confirms a significant distinction between the novice and the expert view of the product and hence confirms the need for addressing such issues. When participants were asked to write down some additional requirements that could be appropriate (PSNRs), they stated 1.75 requirements on average. However, when they were later given an extensive list of 146 PSNRs, on average 31.375 PSNRs were chosen. This clearly shows that novice engineers tend to miss many potentially significant requirements. However, offering many requirements could result in over-constraining. By integrating the method into a decision support system, additional controls and alerts can be implemented to avoid this problem.

7. Conclusions

In the paper, the need for guidance towards eliciting the necessary requirements to be included in the RL is presented first. The need stems from the fact that the product design process can be severely elongated, and hence more expensive, if some necessary requirements are missed when preparing the RL. In this case, usually another iteration of the process needs to be taken in order to establish the requirement in the later phases. We call this problem under-constraining the product. On the other hand, if the product is over-constrained in these early phases of the product design process, the later phases are too limited, which leads to a suboptimal product. Both problems are often connected to the lack of experience of the design engineer.

The new necessity-based method for requirement elicitation and classification is an approach towards avoiding such problems. The proposed method offers a framework for eliciting requirements in a systematic and orderly manner. The purpose of the method is to guide the user towards eliciting a more appropriate RL, i.e. with missing as little necessary requirements as possible. The first step of the method is to define some basic requirements, usually defined for all different products. The method offers 27 so called eFFF properties, which are proposed on the basis of the eFFF approach that takes physical properties of the product (form), connections of the product with its environment (fit) and operational properties (function) into account. Every defined eFFF property becomes an UNR and every UNR is connected to some topics of the PSNR (Table 1). Grouping the UNRs by LCPs and/or components of the product and adding up weights of each PSNR topic show which topics are most probably important for the observed LCP-component couple. The next step is to define some PSNRs from the calculated PSNR topics. Then, all undefined stated requirements are classified as ORs and the RL is written.

It can be seen that with the use of the method along with the requirement elicitation, requirements are also classified as UNRs, PSNRs and ORs. From the practical point of view this classification can help a company establish formal rules or guidelines on requirements that are essential and on who is responsible for supplying some particular piece of information. From the theoretical point of view such a classification is the basis for further investigation of the design process for similar and different products, for discussion on design situations in the early phases of the design process and for more accurate evaluation of the over- and the under-constraining of a product.

The nature of the method itself guides the user away from under-constraining the product. The purpose of the method is to remind the user of the requirements that are important for the designed product. Thus, all the steps focus on avoiding under-constraining. On the other hand, the comparison with industrial RLs yields the borders for over-constraining (Section 6). Once the proposed necessity-based method is implemented in the intelligent support system, these borders can be programmed to alert the user to possible over-constraining. Therefore, the method gives the basis for avoiding the over-constraining of the product.

The case study on photovoltaic panels was an example of the use of the new necessity-based method. The chosen case was topical and it examined the residential solar panel design with the help of a consumer preference study conducted by Chen et al. [50]. It exposed disadvantages, such as time consumption and the possibility of possible misleading the design engineer towards over-constraining the product, as well as advantages like guidance to avoid under-constraining the product, systematic way of eliciting requirements and possibility of incorporating the method in a decision support system. In the case study, all the main steps of the method are clearly shown.

The method was validated and verified by a real industrial case of the design of an air ventilation register box. It showed that the eFFF approach and the condition that all eFFF parts should be defined hold. It also confirmed that the proposed important PSNR topic calculation is appropriate. The appropriateness and contribution of the proposed method was also confirmed by interviews with industry experts. On the other hand, the method was tested by novice design engineers. The results showed that a significant share of issues with under- and over-constraining the product can be overcome by using the necessity-based method. However, in the part of the PSNR definition, some additional alerts to over-constraining could be implemented.

As stated, the existing methods for requirement elicitation mostly ignore the necessity and the content of requirements. There exist some informative lists of possibly important requirements, which do not guide the user through the requirement elicitation process. The requirement classification that we propose is also based on the requirement necessity and can be compared to existing classifications as follows in Table 3:

Table 3 Comparison between the proposed necessity-based method and existing methods for requirement classification

Existing classification	Classification criterion	Similarities to necessity-based method	Differences from necessity-based method
EIA-632 [23]	product's function and LCP	LCP can be incorporated into the necessity-based method, product's function is part of eFFF	discusses already elicited requirements, does not discuss necessity
Weissman et al. [24]	LCP	LCP can be incorporated into the necessity-based method	discusses already elicited requirements, does not discuss necessity
Kano [25]	customer satisfaction according to fulfilling requirements	most of Kano's "required quality" requirements are part of UNR and PSNR and most of Kano's "one-dimensional quality" requirements belong to OR	discusses only customer requirements – all other requirements (such as production or transport requirements) belong to "indifferent quality" requirements and hence ignores requirements' necessity
Dieter and Schmidt [3]	design engineer's options	no apparent direct similarities	completely different aspect of requirement elicitation, discusses already elicited requirements
Hull et al. [26]	product structure hierarchy (with stakeholders' requirements on the top)	in the proposed method stakeholders' requirements are also emphasized and the product is also structured into components	discusses already elicited requirements, does not discuss necessity
QFD [25]	stakeholders' priorities, possibilities for fulfilment, market competition	in the proposed method stakeholders' requirements are also emphasized, in both approaches the production methods are taken into account	discusses already elicited requirements, does not discuss necessity

From the comparison it is clear that the classifications are complementary, since none of the existing classifications discusses the necessity of a particular requirement of a product.

A major limitation of the proposed method is that there are still steps that require certain extent of design engineer's intuition (for example, choosing final UNRs and PSNRs from given topics, choosing the number of requirements at each stage). However, the paper also suggests general guidelines to be followed in these steps. Another limitation is dealing with over-constraining by counting the number of the defined requirements. In some cases a product can in fact be over-constrained with very few requirements defined. For such cases again, some design engineer's rational thinking should be involved. With the use of the proposed method we also cannot claim that all the necessary requirements have been defined. However, we can say that the method reminds the user of some important and product-relevant requirements (or requirement topics) that are very likely to be missed or neglected, especially by design engineers with lack of experience.

Therefore, we can conclude that the previously stated research questions have been answered. We have established a systematic approach towards eliciting a RL, taking the necessity of requirements into account. We have also proposed a method for determining necessary requirement topics for a specific product by calculation. Additionally, we offered a frame for avoiding under- and over-constraining a product.

Further research on the topic is being done in the way of testing the method in practice (industry). The implementation of the method in the decision support system is currently in the process. This implementation will (among many other features) offer an effective tool for avoiding over-constraining the product, for which the theoretical frame was set in the research presented in this paper. Another direction which could improve the method, is also finding more appropriate eFFF properties, PSNR topics and PSNR checklists. The literature sources can be complemented by gathering expert opinions and observing the process in practice.

Indeed, it is possible to argue the pros and cons of specific parts of the new necessity-based method. However, the fact is that this method fills the gap between two well-established groups of methods: the requirement elicitation methods such as [21, 22] that tell the user little about which requirements need to be established, and the requirement classification methods, for instance [26], which classify already elicited requirements and do not answer the question of which requirements are necessary for the product and which are rather optional.

REFERENCES

[1] Booker, J.D., Raines, M. and Swift, K.G., 2001, *Designing Capable and Reliable Products*, Butterworth-Heinemann, Oxford, UK.

[2] Fernandes, J., Henriques, E., Silva, A. and Moss, M.A., 2014, "Requirements change in complex technical systems: an empirical study of root causes," Research in Engineering Design, Published online. DOI: 10.1007/s00163-014-0183-7

[3] Dieter, G.E. and Schmidt, L.C., 2009, *Engineering design,* McGraw-Hill, New York, USA.

[4] Chong, Y.T., Chen, C.H. and Leong, K.F., 2009, "Human-centric product conceptualization using a design space framework," Advanced Engineering Informatics, **23**(2), pp. 149-156. DOI: 10.1016/j.aei.2008.10.003

[5] Pahl, G. and Beitz, W., 1996, *Engineering design: A systematic approach,* Springer-Verlag, London, UK.

[6] Sim, S.K. and Duffy, A.H.B., 2003, "Towards an ontology of generic engineering design activities," Research in Engineering Design, **14**(4), pp. 200–223. DOI: 10.1007/s00163-003-0037-1

[7] Ullman, D.G., 2010, *The mechanical design process,* McGraw-Hill, New York, USA.

[8] Ball, L., Evans, J. and Dennis, I., 1994, "Cognitive Processes in Engineering Design: a longitudinal study," Ergonomics, **37**(11), pp. 1753-1786. DOI: 10.1080/00140139408964950

[9] Rowe, P., 1987, *Design Thinking*, MIT Press, Cambridge, MA, USA.

[10] Ogawa, T., Nagai, Y. and Ikeda, M., 2009, "An ontological approach to designers' idea explanation style: Towards supporting the sharing of kansei-ideas in textile design," Advanced Engineering Informatics, **23**(2), pp. 157-164. DOI: 10.1016/j.aei.2008.10.001

[11] Morrow, W.R., Mineroff, J. and Whitefoot, K.S., 2014, "Numerically Stable Design Optimization With Price Competition," Journal of Mechanical Design, **136**(8), 081002 (17 pages). DOI: 10.1115/1.4025703

[12] Chau, K.W. and Albermani, F., 2004, "Hybrid knowledge representation in a blackboard KBS for liquid retaining structure design," Engineering Applications of Artificial Intelligence, **17**(1), pp. 11-18. DOI: 10.1016/j.engappai.2003.11.007

[13] Atman, C.J., Chimka, J.R., Bursic, K.M. and Nachtmann, H.L., 1999, "A Comparison of Freshman and Senior Engineering Design Processes," Design Studies, **20**(2), pp. 131-152. DOI: 10.1016/S0142-694X(98)00031-3

[14] Eagan, R.J., Allen, B.E., Caudill, C.D., Howard, R.A., Hunter, J.S., Magee, C.L., Ostrach, S. and Rouse, W.B., 2001, *Approaches to* improve *Engineering Design*, The National Academies Press, Washington, DC, USA.

[15] Novak, M., 2012, "Computer Aided Decision Support in Product Design Engineering," Tehnicki Vjesnik-Technical Gazette, **19**(4), pp. 743-752.

[16] Sim, W.W. and Brouse, P.S., 2014, "Empowering Requirements Engineering Activities with Personas," Procedia Computer Science, **28**, pp. 237-246. DOI: 10.1016/j.procs.2014.03.030

[17] Adlin, T. and Pruitt, J., 2010, *The Essential Persona Lifecycle: Your Guide to Building and Using Personas*. Morgan Kaufmann, Boston, USA.

[18] Arnowitz, J., Arent, M. and Berger, N., 2007, *Effective Prototyping for Software Makers*, Elsevier, San Francisco, USA.

[19] Chen, S.L. and Tseng, M.M., 2005, "Defining specifications for custom products: A multi-attribute negotiation approach," CIRP Annals - Manufacturing Technology, **54**(1), pp. 159-162. DOI: 10.1016/S0007-8506(07)60073-0

[20] Ouretani, M.Z and Gzara, L., 2008, "Tracking product specification dependencies in collaborative design for conflict management," Computer-Aided Design, **40**(7), 580-597. DOI: 10.1016/j.cad.2007.07.002

[21] Azadegan, A., Papamichail, N.K. and Sampaio P., 2013, "Applying collaborative process design to user requirements elicitation: A case study," Computers in Industry, **64**(7), pp. 798-812. DOI: 10.1016/j.compind.2013.05.001

[22] Meth, H., Brhel, M. and Maedche, A., 2013, "The state of the art in automated requirements elicitation," Information and Software Technology, **55**(10), 1695-1709. DOI: 10.1016/j.infsof.2013.03.008

[23] GEIA, 1999, *Processes for Engineering a System, EIA-632*, Government Electronics and Information Technology Association, Arlington, USA.

[24] Weissman, A., Petrov, M. and Gupta, S.K., 2011, "A computational framework for authoring and searching product design specifications," Advanced Engineering Informatics, **25**(3), 516-534. DOI: 10.1016/j.aei.2011.02.001

[25] Cohen, L., 1995, *Quality Function Deployment: How to make QFD work for you,* Addison-Wesley, New York, USA.

[26] Hull, E., Jackson, K. and Dick, J., 2005, *Requirements engineering,* Springer, London, UK.

[27] Madu, C.N., 2006, *House of Quality in a minute: Quality Function Deployment,* Chi Publishers, Farfield, USA.

[28] Kuusela, J. and Savlainen, J., 2000, "Requirement Engineering for Product Families," ICSE, pp. 61-69. DOI: 10.1145/337180.337189

[29] Gomaa, H. and Kerschberg, L., 1995, "Domain Modeling for Software Reuse and Evolution", in: *Seventh International Workshop on* Computer-*Aided Software Engineering,* pp. 162-171. DOI: 10.1109/CASE.1995.465317

[30] Deets, D.M., 1985, *The use of Form, Fit, and Function in the acquisition of major weapon systems (Thesis)*, Naval Postgraduate School, Monterey, California, USA.

[31] Rosensteel T.E., 1988, *An evaluation of perceptions of Form, Fit, Function (F3) standardization on the standard inertial navigation unit (STD INU) program (thesis)*, Department of the Air Force Air University, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, USA.

[32] Odierno, T.R., *Maintenance of supplies and equipment: Army modification program (Army Regulation 750-10),* Headquarters Department of the Army, Washington, DC, USA.

[33] Criscimagna, N.H., 2005, "Form, fit, function, and interface – an element of an open system strategy," The Journal of the Reliability Analysis Center, first quarter, pp. 7-14.

[34] ElMaraghy, H.A., Barari, A., Knopf, G.K., 2004, "Integrated Inspection and Machining for Maximum Conformance to Design Tolerances," CIRP Annals - Manufacturing Technology, **53**(1), pp. 411-416. DOI: 10.1016/S0007-8506(07)60728-8

[35] Baker, A., 2013, "Configurable obsolescence mitigation methodologies," Procedia CIRP, **11**, pp. 352-356. DOI: 10.1016/j.procir.2013.07.013

[36] Chakraborty, P.S., Sarkar, B. and Majumdar G., 2013, "Group decision making for a manufacturing organization considering intensity of preference," Advances in Production Engineering & Management, **8**(3), pp. 149-156.

[37] Harih, G., 2014, "Decision support system for generating ergonomic tool-handles," International Journal of Simulation Modelling, **13**(1), pp. 5-15. DOI: 10.2507/IJSIMM13(1)1.234

[38] Kaljun, J., 2014, "Intelligent support for defining aesthetical, ergonomical and material properties of designed product," Technical Gazette, **21**(4), pp. 835-842.

[39] Vinodh, S., Jayakrishna, K., Vishwajeet, K. and Dutta, R., 2014, "Development of decision support system for sustainability evaluation: a case study," Clean Technologies and Environmental Policy, **16**(1), pp. 163-174. DOI: 10.1007/s10098-013-0613-7

[40] Ayadi, M., Affonso, R.C., Cheutet, V., Masmoudi, F., Riviere, A. and Haddar, M., 2013, "Conceptual Model for Management of Digital Factory Simulation Information," International Journal of Simulation Modelling **12**, pp. 107-119. DOI: 10.2507/IJSIMM12(2)4.233

[41] Kwong, W.Y., Zhang, P.Y., Romero, D., Moran, J., Morgenroth, M. and Amon, C., 2014, "Multi-Objective Wind Farm Layout Optimization Considering Energy Generation and Noise Propagation With NSGA-II," Journal of Mechanical Design, 136(9), pp. 091010. DOI: 10.1115/1.4027847

[42] Gao, F., Xiao, G. and Simpson, T.W., 2010, "Identifying functional modules using generalized directed graphs: Definition and application," Computers in Industry, **61**(3), pp. 260-269. DOI: 10.1016/j.compind.2009.09.007

[43] Saaksvuori, A. and Immonen, A., 2008, Product Lifecycle Management, Springer, Heidelberg, Germany.

[44] Di Foggia, M. and D'Addona, D.M., 2013, "Identification of critical key parameters and their impact to zero-defect manufacturing in the investment casting process," Procedia CIRP, **12**, pp. 264-269. DOI: 10.1016/j.procir.2013.09.046

[45] Sakundarini, N., Taha, Z., Abdul-Rashid, S.H. and Ghazilla, R.A.R., 2014, "Incorporation of high recyclability material selection in computer aided design," Materials and Design, **56**, pp. 740-749. DOI: 10.1016/j.matdes.2013.11.027

[46] McKay, A., de Pennington, A. and Baxter, J., 2001, "Requirements management: a representation scheme for product specifications," Computer-Aided Design, **33**(7), pp. 511-520. DOI: 10.1016/S0010-4485(01)00050-1

[47] Savio, E., Carmignato, S. and De Chiffre, L., 2014, "Benefit quantification of interoperability in coordinate metrology," CIRP Annals – Manufacturing technology, available online. DOI: 10.1016/j.cirp.2014.03.037

[48] Golay, M.W., 2000, "Improved nuclear power plant operations and safety through performance-based safety regulation," Journal of Hazardous Materials, **71**(1-3), pp. 219-237. DOI: 10.1016/S0304-3894(99)00080-1

[49] Haug, A., Hvam, L. and Mortensen, N.H., 2012, "Definition and evaluation of product configurator development strategies," Computers in industry, **63**(5), pp. 471-481. DOI: 10.1016/j.compind.2012.02.001

[50] Chen, H.Q., Honda, T. and Yang, M.C., 2013, "Approaches for Identifying Consumer Preferences for the Design of Technology Products: A Case Study of Residential Solar Panels," Journal of Mechanical Design, 135(6), 061007 (12 pages). DOI: 10.1115/1.4024232

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