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REQUIREMENTS ON ENGINEERING DESIGN METHODOLOGIES

Alexander Keller[1], Hansgeorg Binz[1]
(1) Universitaet Stuttgart, Germany

ABSTRACT

Based on a literature research on engineering design research, engineering design methodologies and their development, requirements on engineering design methodologies are reasoned, grouped into a checklist-type catalogue and evaluated for their interrelations. The set of requirements aims at the assessment of individual methodologies, the comparison of different methodologies and the support of the development of new methodologies. The requirements have been found to be reasonably independent from each other in general whereas a group of five proved to be prominent by showing, in contrast to the rest, frequent interdependencies with other requirements.

Keywords: requirements, design methodology, design methods, design process, design science, design research, mechatronics

1 INTRODUCTION

Constructs of abstract and theoretical nature can only be legitimised as engineering design methodologies if they can cope with requirements resulting from both the methodologies' abstract and theoretical nature and the real design situations they are aimed at. Explicitly describing what is required of an engineering design methodology is an inevitable prerequisite for assessing its suitability for the design situations in question, i.e. for its validation [1] - [7]. The task of validating methodologies and methods in engineering designing has ever since imposed a great challenge on design researchers. No final solution can be presented within the scope of this article. A contribution to the premises for this task is made, however.

This paper clarifies in a structured manner the origin of requirements on engineering design methodologies, presents the different requirements and reasons certain interrelations between requirements. Among other aspects especially those originating from engineering design science, design research, design practice and philosophy of science are taken into account. Regarding specific fields of application for a methodology mechatronical demands are emphasised.

At first a definition of "methodology" is given and the distinction between "method" and "methodology" is made. The second section explains the aim and use of the results. The third section deals with the methods applied in the research of requirements on engineering design methodologies. The resulting requirements of section four are presented in eight groups: Revisability, Practical Relevance & Competitiveness, Scientific Soundness, Comprehensibility, Usefulness, Problem Specificity, Structure & Compatibility, and Flexibility. A brief summary of the research results is given in the conclusion.

Definitions of the term "methodology" are given in the relevant literature [8] - [29]. For an unambiguous understanding it has to be pointed out that within this paper the term "methodology" is used referring to a structured set of procedures (methods) (in German: *Methodik*) rather than to the science of methods (cf. [25], [26]) (in German: *Methodologie* or *Methodenlehre*).

From the philosophy of sciences' point of view *methodology* (in its meaning as science of methods or *Methodologie*) was originally related to logics and didactics as a measure to teach the concepts of logics and later on connote a directive pointing towards the possibly best fitting method within a science or art (*Methodik*) [28]. Thus a methodology can be understood from the philosophy of sciences' point of view as a canon of rules comprising a certain set of methods [28]. A method is a rule-based pursuit of objectives ensuring the proper modality of examination [29]. The resemblance of the different meanings of methodology and that of the not only etymological related *method* as well as their use is similar to the field of engineering design science.

In the engineering design science the term methodology describes a directive for a systematic approach with specific instructions for the design of technical systems. The instructions can include, but are not limited to, prescriptive or descriptive methods of different domains, the relations between these methods, schedules, rules, principles and strategies [1], [9], [10]. In a more general way the term methodology is sometimes also used for methods such as Quality Function Deployment (QFD), representing an umbrella for sub-methods [16], whereas a minority opinion claims methodologies such as Engineering Design by Pahl and Beitz (in German: *Konstruktionslehre*) [8] to be comprehensive methods [23].

2 OBJECTIVES

The work presented in this paper has been performed in preparation of a project aiming at the development of a methodology for the design of novel machine elements in an interdisciplinary context. The task is to structure the design of these elements and the designing with these machine elements (or more generally, design elements, since not being limited to building machines), that utilise both the integration of sensor, actor, control and/or structure (as known from mechatronics or adaptronics) and the controllably variable properties of smart materials. Due to the interdisciplinarity of the project a co-ordination has to take place, starting with the definition of requirements on a common way of conduct (or less neutral: *methodology*), a comparison of the usually practised procedures and finally a selection of a common strategy.

In engineering design practice dealing with requirements is common state-of-the-art across the domains being involved and the entities to be designed, be it soft- or hardware in mechanical, electrical, software or civil engineering. The requirements are essential for the assessment and especially the validation of the outcome of the design process. From an economical point of view every action or event taking place in a business consumes resources and thus can be interpreted as a process black-box with inputs, activities and outputs. Certain invariable prerequisites might affect the activities. A thorough understanding and knowledge of the input, the activities and the output is required, to optimise the process (cf. [3]), that is minimising inputs and maximising outputs or in general reducing the consumption of resources per outcome. Performing such an optimisation implies the existence of criteria to determine the degree of improvement. Improvement does only matter where a process parameter affects the efficiency of the process. Terms such as minimising, maximising or optimisation do not by their own imply that a minimum, a maximum or an optimum does exist at all or could be found easily.

As it is said in [2] *"the overall aim of engineering design research is to support industry by developing knowledge, methods and tools which can improve the chances of producing a successful product"* (also cf. [47]). Designing takes place in a process as described above. A design methodology, being a result of engineering design research, is a blueprint for such a design process. Assessing this process requires appropriate criteria. This paper suggests a checklist-type catalogue of relevant generic requirements on an engineering design methodology that aims at supporting the development of an engineering design methodology from the early phases up to the validation of the methodology. The generic character of the proposed requirements allows for an assessment of individual methodologies or a comparison of different methodologies based on formalised criteria.

As seen from the present state of engineering design research these criteria can only be interpreted as indicating that a methodology meeting them might "*improve the chances of producing a successful product"* more than one not meeting them (cf. [50] and [52]). No empirical study has been conducted, yet, to test for this within the scope of the research underlying this study, nor is there any study doing this known to the author of this paper. Proving the non-existence of another methodology, that allows for an at least as successful product, will fail anyway according to [49], however. The set of requirements given beneath does not tacitly mean that each element is of equal importance in different specific methodologies. This set does not include means for resolving potential conflicts of objectives between single elements, either.

3 METHODS

According to the background of this paper the analysis of the state-of-the-art methodology research had an emphasis on mechatronics and adjacent domains in as far as aspects inherent to the topic of the project were concerned [21], [30] - [39]. Beyond this the state-of-the-art engineering design research was considered with regard to questions concerning all weak or non-domain specific aspects [2], [4] - [6], [15], [19], [20], [40] - [61].

When it comes to analysing publications claiming the development of a methodology for a specific class of engineering design problems (and in the optimal case the successful validation of the methodology), with most of them being Ph.D.-theses, it appears that none is found reporting a failure in validating the proposed methodology. It is not the objective of this study to examine and explain this effect. It should be kept in mind, yet, that the analysis might suffer from some kind of publication bias. Furthermore, attention has to be paid to the number of implementation projects the methods or methodologies were tested in (cf. [45]), which often is just a single project.

As given by the definitions methods are subsets of a methodology. Performing a bottom-up approach those targets and requirements, that have to be met by certain methods included in a superior methodology, are of relevance for the superior methodology, too. Since in general a certain methodology incorporates more than one method, a multitude of targets and requirements cumulates from the plenitude of methods. This multitude is likely to cause conflicts of objectives on the methodology level. As, in accordance to what was said in the introduction, a method is faced with theoretical and practical requirements (the latter resulting from a specific problem to be solved by the method) (cf. [55]), for practical reasons of the research underlying this paper only the theoretical requirements on a method were taken into account for determining requirements on a superior methodology.

This leaves the conflicts of objectives, if revealed, to be settled or a least to be dealt with. Suggestions how this can be achieved are made in the results section of this paper. Despite this problem these considerations advise taking requirements on methods also into account as requirements on the superior methodology. This demand was implemented by considering studies covering research both on methodologies and methods.

4 RESULTS

The requirements on engineering design methodologies can be classified into eight groups, called A to H (without prioritising them) (Table 1) (cf. [40], [47]).

Table 1. Groups of requirements on engineering design methodologies

Group	Group Description	Grouped Items
A	Revisability	Validation Verification
B	Practical Relevance & Competitiveness	Innovativeness Competitiveness
C	Scientific Soundness	Objectivity Reliability Validity
D	Comprehensibility	Comprehensibility Repeatability Learnability Applicability
E	Usefulness	Effectivity Efficiency
F	Problem Specificity	Problem Specificity
G	Structure & Compatibility	Handling Complexity Problem Solving Cycle Structuring Compatibility
H	Flexibility	Flexibility

4.1 A: Revisability

Any scientific statement has to be revisable by the means acknowledged as appropriate within the associated community. When speaking of requirements and engineering design, the common strategy used in product development – testing the compliance of a product in the order of verification against specifications and validation against requirements – comes at first to mind. Transferring this concept to a methodology instead of a product means (cf. [3], [51]) to check firstly whether a methodology or the actual engineering process derived from it (disregarding in this gedankenexperiment the potential flaws in implementation) does things right and secondly whether the right things are done [4], [19], [20], [43] - [45], [47]. From the point of view of someone who is to arrange a methodology for a certain class of assignments the reverse order of conduct applies, the definition of requirements ranks first.

Along with requiring something the question comes how to perform the test for compliance with the requirements, which means the statement must be assessable from an internal and an external point of view. Internally, the statement must be formulated in a style that actually allows assessment, and, externally, means have to be at hand to perform the assessment. Providing these means is the task of engineering design research (e.g. [1], [2], [4], [47]).

The concept of validating statements as it is broadly used in natural and engineering sciences is based on the research of the philosophy of sciences, especially the theories of Popper reasoning the revision of theories by rigorous falsification and refusing to determine probabilities of a concept being valid [49]. However, since engineering design and its processes have to deal with diffuse objectives and objects and therefore use amongst others intuitive methods, whose mode of operation within the human brain is little understood so far, a revision of methodologies based solely on the validation as proposed from a falsificationist point of view is not satisfying (cf. [50]). Whereas the evaluation methods and tools as established in social and human sciences have to be taken into consideration as possible means for revising methodologies, too. This point of view is for example represented by Pedersen et al. stating that *"scientific knowledge [is] socially justifiable belief"* and knowledge validation is *"a process of building confidence in its usefulness with respect to a purpose"* [4].

4.2 B: Practical Relevance & Competitiveness

A methodology must feature practical relevance and competitiveness. At first this means that a lack of methodology must prevail in a certain field of application, in other words a demand for a methodology has to be met. If there is such a demand, this implies that no existing methodology satisfies the demand or the degree of satisfaction is not sufficient, yet (cf. [7]).

As to the first alternative a new methodology would provide some kind of "innovation" (not to be confused with the way the term "innovation" is often connoted with the commercial success of a novelty) (cf. [43]). With regard to the second alternative the new methodology has to prove its competitiveness in comparison to the existing competing methodologies. That is, the application of the new methodology should provide at least as good results as competing methodologies (cf. [50]). When it comes to verifying and validating a methodology the assessment against competitors should be considered as an important benchmark for reasoning a methodology [50].

4.3 C: Scientific Soundness

In a very condensed way a methodology can be interpreted as a set of hypotheses or a single even more complex hypothesis. Bearing that in mind, with respect to the scientific soundness of a methodology three aspects are of importance [50]: Objectivity, reliability and validity. These three aspects especially refer to requirements on the process of hypothesis falsification. A hypothesis which was tested in a manner not meeting the standards of objectivity, reliability and validity cannot be considered as objective, reliable and valid. Thus objectivity, reliability and validity are suggested as appropriate requirements to ensure scientific soundness in the shape of an objective, reliable and valid methodology. This requirement of scientific soundness should not be confused with establishing a primacy of, for example, engineering design research carried out in an academic environment over research primarily conducted in field in industry. Both contribute equally to the advancement in research, but both have to meet those scientific standards in their approach and conclusions, that are appropriate to the research methods used (cf. [47]).

In natural sciences objectivity refers to the independence of an observation or description from the person performing the observation or description and the absence of personal opinion or interpretation. In detail objectivity means that a methodology has to be consistent by providing identical instructions in identical situations. Albeit this requirement for consistency, it has to be acknowledged that, especially in engineering design with its highly empirical and creative moment, conflicting truths and solutions do exist [43]. A methodology must keep neutrality with respect to the solution of a problem, i.e. it must not bias the designer in selecting solutions with a (implicit) pre-configuration of preferences. The designer should be left to decide on his/her own or, at least, implications on a configuration of preferences have to be revealed as clearly as possible [6], [43]. To some extent every Design-For-X/Design-To-X (DFX/DTX) guideline imposes a kind of bias by deliberately overemphasising “X”-aspects as compared to any non-“X”-aspects.

A methodology should remain independent from interpersonal and intrapersonal predispositions and thought processes [19], [43]. This demand is in some way linked to not biasing the designer. Considering a fictional methodology running fully computer automated, firstly consistency was handled, secondly, unlike with human designers, pre-configuration of preferences was necessary and finally interpersonal and intrapersonal effects were eliminated. Such a form of masking personal properties of human designers such as expert knowledge or abilities is not possible in the real world; in an inevitable manner these properties will have an influence on the application of the methodology. However, the methodology should not prescriptively anticipate the absence or presence of such properties or certain types of thought processes.

From the present state-of-art in product and resource life cycle research one would be well advised to consider the relevant life cycles within a methodology completely (cf. [3]). This is a very strict requirement for several reasons. On the one hand a methodology is a model or prototype of an ideal process. Every model is a simplification of reality, focussing on specific aspects and ignoring others in order to control complexity. Thus in every model setup a rivalry exists between the objectives of completeness and complexity. On the other hand the specification of a certain product to be developed might provide detailed preferences legitimising to neglect certain phases of a life cycle. In both cases, however, according to what was said about avoiding the pre-configuration of preferences, the methodology should consider full life cycles and the decision about neglecting specific parts of the methodology dedicated to the full life cycle should be left to the designers.

Reliability means that an analysis reaches certain formal standards and is free of errors. Further reliability includes the repeatability of an analysis, which especially requires the knowledge, denomination and control of the influencing factors of the analysis. Accordingly, any input to the analysis (such as information or equipment) must be relevant and reliable. These aspects hold unrestrictedly true for a methodology, as well.

The term validity finally is coined by the congruence of the objectives the methodology was intentionally set up for on the one side and what the methodology is actually able to accomplish on the other side. This requires a distinct and explicit description of the objectives to validate against. Furthermore this description should easily allow differentiating between the set of problems a methodology is eligible for and for which it is not.

4.4 D: Comprehensibility

Several requirements concerning the comprehensibility and related aspects have to be fulfilled by a methodology. These are at first comprehensibility itself and then repeatability, learnability and applicability.

The methodology must be comprehensible both from an a priori and an a posteriori point of view. The a priori view should show a clear description of the methodology explaining for example why, when, which and how things *have to be done* [36], [43]. The a posteriori view documents why, when, which and how things *have been done*. These two views are strongly related to the requirement given in the revisability section, namely the possibility for validation as a comparison of the a priori and the a posteriori view. Hence a methodology must provide means supporting the continuous documentation of the course of actions taken and the achieved results. At present this will most commonly require computer aided systems, such as Engineering Data Management systems [56]. This supports the formalization, the externalization of the design process [26] and consequently an increased transparency of the process, too [42] (cf. [40]). Furthermore formalization, externalization and transparency aim at initialising and supporting a self-amplification effect due to the learning processes taking place both within the user and the organisation [36], [52].

The next requirement, repeatability, is directly based on those just outlined, since a repetition requires a precise description of what is to be repeated and a description of what the outcome so far was if you want to compare the results of two or more repetitions. Repeatability should be as unconditional as possible regarding the prerequisites, but is dependent on how strict the limitations of the application of the underlying methodology are formulated [43].

Learnability can be understood as considering the same aspects as teachability (as for example stated in [57]), but being formulated from an opposite point of view. The first aspect of learnability is that a methodology must be understandable, which can be split into four criteria. The way of representing the methodology has to be governed by semantics and syntax. This is regularly no problem if the representation is given in a textual form. It becomes more difficult if a graphical or combined representation is chosen, where the semantics and syntax are not clear to every one at once. Then an explicit explanation and definition of semantics and syntax should be included [36], [57]. In cases where standardised representation methods are used such as Unified Modelling Language (UML), Structured Analysis and Design Technique (SADT), Integrated Definition (IDEFx), flow charts (e.g. structured according to DIN 66001 [58]), Petri nets or state charts, the required level of detail in additional explanation might be lower than if un-standardised representations are employed. This requirement does not from the outset conflict with using a graphical representation that is also suitable for promoting a methodology as a visual eye catcher. Secondly, the concepts used to describe the methodology should originate from the sphere of concepts of the domains involved in the design process [44]. This can conflict with the third criterion that semantic ambiguities have to be avoided, which occur if terms have different meanings in different domains or are not generally known across different domains (very prominent for example between engineering and non-engineering domains) [21], [44]. The more an engineering design process relies on interdisciplinary work as for example in mechatronics the more important this aspect becomes. Finally it should be possible to use a methodology as intuitively as possible, that is the effort spent by the users on learning the methodology should be kept minimal (at least in relation to the expected potential outcome of the methodology) [19], [52], [51]. In total the criteria for being understandable are closely related to those concerning the comprehensibility as described above in this section.

The second aspect of learnability requires that the statements of the methodology are meaningful, that is, based on expertise, appropriate to the domains and relevant to the problem, chronological sound and logical. This aspect can be interpreted to a certain extent as a formalisation of the prior call for an intuitive applicability. At this point the consistency as explained in the section on scientific soundness may be brought to attention, again, which concerns both meaningfulness and semantic and syntactical representation. The third aspect of learnability concerns providing a knowledge base. This knowledge base has to comprise both the required knowledge of the subject of the design process and the knowledge of the methodology and methods involved in the problem solving [10], [41], [42]. In other words, a methodology should clearly point out and reference which knowledge is required for applying the methodology. In analogy to the knowledge base the required base of competencies has to be stated [42]. With the term learnability we are so far focussing on the persons learning and their needs of understanding these aspects. But looking from the opposite point of view, the teaching, should not be neglected either. A strategy should be present outlining how a methodology can be implemented into a socio-technical system. This strategy has to explain how the change from the existing procedures to the new methodology should progress [43]. Furthermore, the strategy requires, but is not limited to, a concept of motivating the potential users of the methodology to actually participate in the roll-out and persistent application of the methodology, i.e. positive stimuli from the application of the methodology must be received by the persons involved [51], [52]. This is closely related to the self-amplifying learning process mentioned before.

Applicability has to face the complexity of the problem in question within the design task as well as the complexity of implementing or teaching the methodology into an organisation [42]. The methodology must provide means that are adequate for handling both complexities. This represents the operationalisation of the implementation strategy and will unpreventably be challenged by ubiquitously existing objective or subjective, personal or organisational resistances to change [53], [57]. But in the end, a methodology is of little use, if it cannot be put into effect due to the failure in overcoming these resistances to change or due to mismatching the complexities.

4.5 E: Usefulness

Usefulness covers two major criteria: Effectivity and efficiency. Effectivity in general relates an actual result to the desired result. Efficiency relates the effort spent in producing a result to the use provided by the result. Thus distinct criteria for the assessment of the desired result, the real result, the effort spent and the use of the product are necessary. Applying the concepts of effectivity and efficiency to the assessment of a methodology can be done in a direct manner by examining parameters of the process of designing (e.g. time or cost spend for producing results) or indirectly by assessing the product of the process (cf. [47]).

The effectivity of a methodology is a major criterion to select one methodology from among many. This requires that the field of application, the limits of application, the suitable objects of application and the prerequisites for the application of a methodology are made clear beforehand [20]. As far as the assessment of effectivity is concerned, Ehrlenspiel adds an interesting point to what was said in the last paragraph when he claims a methodology to be effective if it is perceived effective by the users [15] . From this follows that effectivity is dependent on the prospective acceptance of the methodology by the user, the reduction of intrinsic and extrinsic barriers to apply the methodology and the ability to motivate users to apply the methodology (cf. [51]).

A methodology, which will help to consider the pros and cons of its application before you come to a decision, should provide measures for predicting the potential use and effort of the application of the methodology [3], [52]. Among others the effort to be spent includes time, staff and its qualification, information, software and hardware equipment, and external consulting [42]. Furthermore, it has to be considered that the implementation of a new methodology consumes resources likewise, especially if the operational and the organisational structure have to be realigned [3], [54], [57].

To achieve a learning effect, it has to be taken into consideration where to place a methodology between the polarities of a very abstract (generic) description, that apparently could cover a very wide range of possible assignments due to its universality, and a rather specific description with a narrower range. From a practical point of view, the less decisions have to be taken the easier a methodology is applied. But it has to be kept in mind that a methodology should not bias the designer in his/her decisions by too many prescriptions. On the level of methodology as opposed to the level of methods the emphasis should lie on structuring the assignment by pointing towards appropriate methods, not on prescribing methods or solutions.

In a very general way this is summed up by demanding a methodology to promote factors of positive influence on the design process, to suppress factors of negative influence on the design process and to raise awareness of the unavoidable factors of negative influence [2].

4.6 F: Problem Specificity

Within the spectrum of a most generally and universally formulated methodology on the one end and a very specific one being hardly distinguishable from a method on the other end, a methodology must display a problem specificity that allows a potential user to recognize that this methodology might qualify and be relevant for his/her assignment. This has to be differentiated from the comprehensibility and transparency mentioned in section D referring to the internal view of a methodology, that is if a methodology was selected (for certain external reasons governing problem specificity), its further course of action is clear a priori and a posteriori.

To give an example of problem specificity a closer look is taken at the field of mechatronics. Specific aspects in this domain concern horizontal and vertical continuity of the development process across domains and across development phases [32], especially providing consistent interdisciplinary model building approaches [31], [32], [38] and according model data management and simulation tools [34], modularising systems [35], managing knowledge [3], [30], [36] and decision support for the evaluation of candidate solutions and the selection of manufacturing processes [37].

4.7 G: Structure & Compatibility

The demand for a methodology providing structure and compatibility results from a methodology having to abstractly represent the dynamics of a (creative) process and structure the design problem [55]. If an engineering design assignment to be solved is completely new and ill structured, it can be regarded as a problem, which is characterised by complexity. If a transfer from a prior assignment can be made, the assignment at hand is not entirely new or it is already well structured, it can be considered a task [22], [42], [43], [45]. A methodology should contribute to reducing the complexity of the problem by structuring it in order to transfer it into a task. However, when reducing the complexity, attention has to be paid that the statements made by the simplified structure still have to be meaningful in the context of the original assignment. That is, when mapping the original ill structured assignment by means of the methodology at hand into a well structured task, the solution of the derived assignment (the task) must provide a valid solution to the original assignment (the problem), too. An oversimplification of the original problem would be futile.

The issue of structuring an assignment becomes especially evident if it comes to inter- and multi-disciplinary assignment handling such as mechatronics. Different domains have to be coordinated in many ways and compete with different solutions to a problem which each bear repercussions on the other domain's solutions. It has to be stressed that "different domains" is not just limited to different domains of engineering sciences but comprises, at least, all domains that deliver results to a development process in a company, such as the different fields of economics or jurisprudence [44].

Transferring a problem into a task is not only supported by structuring within one assignment, but also by transferring lessons learned from one assignment to another one. This point is related to the learning process a methodology should initiate and promote and the knowledge and competencies base a methodology has to take into account and extend.

The aspect of structuring or transferring a problem into tasks is not limited to clustering an assignment into sub-assignments but it includes also structuring the universe of methods and tools into a first group of those that are suitable for the problem(s) at hand, a second group of those that could be suitable or at least could be adapted to the problem and finally those that are completely inappropriate (cf. [13]). This structure should regard, besides the aspect of effectivity just described, the aspect of efficiency and try to point out the methods and tools simplest to use [59].

Since neither structuring the assignment, structuring the methods nor matching both can be prescribed in a general valid manner and the quality of a first application of the matched method or tool to the assignment is likely to be not satisfying at the first attempt a methodology must reproduce and consider the problem solving cycles that are inevitable within the sequence of actions in reality.

A methodology must be compatible in several different ways, of which not all must apply at the same time with the same intensity under all circumstances but potentially contribute to a methodology's competitiveness and universality representing a holistic approach. Obviously, referring to what was said before in sections E and F, universality and specificity are to some extent antagonistic.

A methodology has to regard different technical domains and their specific methods and tools (such as DFX/DTX, CAx methods, Project Management tools). A methodology should provide for an adequate variety of different assignments, which can be broken down into four aspects: Firstly handling different sets of objectives, secondly coping with sets of controversial objectives, thirdly meeting dynamic assignments or objectives that keep changing during processing the assignment and, finally, treating uncertain or ill-defined objectives [19], [42], [59]. Furthermore, considering the cognitive abilities and behaviour patterns by aligning the sequence of actions of the methodology with the human way of thinking allows for an intuitive practice of the methodology [19], [42] and by this facilitates the learnability of a methodology. Finally, a methodology and the operational and organisational structure as well as the business model are interdependent [44].

4.8 H: Flexibility

It was mentioned before, that a methodology should not bias the designer in his/her decisions. So far, this argument was relevant in relation to his/her engineering design decisions concerning the design object. On top of this a methodology must feature some flexibility in terms of degrees of freedom for the designer to choose from alternative combinations of methods and their sequence within the framework of suggested methods [1], [16], [19], [36], [42]. This is a more general formulation of the requirement of providing a problem solving cycle, which has a different emphasis, however: The problem solving cycle focuses on improving a result by repeating one distinct sequence, whereas a sequence in general can be any combination of elements, which amongst others could indeed include a repetition of identical sub-sequences. Its focus is on the freedom of choice of the designer regarding the course of action in contrast to the improvement of the results of a prior cycle, yet. Since aim and origin of these two requirements are different, they do not of necessity exhibit a conflict of objectives.

It was found, that successful designers show a consistent and at the same time flexible behaviour by adapting their procedure to changing requirements without losing their target out of sight [42]. The designers should be free to choose alternative methods or tools. Skipping or repeating steps, chronically parallelising or serialising of steps or coupling of steps within the methodology should be possible where appropriate and left to the designer's judgement [36]. This leads for example towards a description of a methodology, that explicitly points out its possible iteration loops or problem solving cycles or identifies an ideal, prototypical path through its phases with mentioning alternative ones at the same time (rigid prescription of sequence in [15]; rather underemphasised in [60], [61]; very explicitly e.g. in [16]; a proposal with no sequence prescribed at all for a given set of methods in [42]).

Furthermore, it should be possible to add phases not yet sufficiently considered and to cluster phases in order to capture partial results from the design process. The perspective of flexibility is particularly important for the implementation of a methodology into the operational and organizational structure, the coordination of and the communication within the engineering process and the problem specificity. In fact it has to be admitted, that flexibility can in some way be in contrast to the demanded problem specificity and the demand for a methodology that is not too general, i.e. too abstract.

Finally, since design processes are amongst other factors driven by the designers' creativity, the available flexibility helps to generate motivation and freedom for creative solution finding.

4.9 Interpretation of the set of requirements

The set of requirements and the interdependencies between its elements are summarised in the methodology requirements matrix given in Table 2. Considering eight groups with a total of 19 distinct requirements a total of 171 relations each with three possible different values (A influences B; B influences A; A and B are of mutual influence) would be possible.

Table 2. Groups of requirements on engineering design methodologies and their interdependencies (Legend for the matrix section: Blank boxes: no direct interrelation; left arrow ←: Item in row is influenced by item in column (e.g. Validation A1 is influenced by Comprehensibility D1); up arrow ↑: Item in row influences item in column (e.g. Comprehensibility D1 influences Problem Specificity F1); crossing left and up arrows ✣: Items in row and column are of mutual influence (e.g. Reliability C2 and Validity C3 are of mutual influence). Note: The matrix section of Table 2 is skew symmetric)

Group Description	Grouped Items	Icon	Validation A1	Verification A2	Innovativeness B1	Competitiveness B2	Objectivity C1	Reliability C2	Validity C3	Comprehensibility D1	Repeatability D2	Learnability D3	Applicability D4	Effectivity E1	Efficiency E2	Problem Specificity F1	Handling Complexity G1	Problem Solving Cycle G2	Structuring G3	Compatibility G4	Flexibility H1	Frequency of being influential	Frequency of being influenced
Revisability	Validation	A1								←													1
	Verification	A2								←													1
Relevance & Competitive-ness	Innovativeness	B1																					
	Competitiveness	B2																					
Scientific Soundness	Objectivity	C1						←			←							←		←	←		5
	Reliability	C2					↑		✣	✣												3	2
	Validity	C3						✣														1	1
Compre-hensibility	Comprehensibility	D1	↑	↑				✣				←			←	↑						4	3
	Repeatability	D2					↑															1	
	Learnability	D3								↑			↑	✣	←					←	↑	4	3
	Applicability	D4										←											1
Usefulness	Effectivity	E1										✣										1	1
	Efficiency	E2								↑		↑					↑			✣		4	1
Problem Specificity	Problem Specificity	F1								←									↑		←	1	2
Structure & Compatibility	Handling Complexity	G1													←				↑			1	1
	Problem Solving Cycle	G2					↑															1	
	Structuring	G3														←	←						2
	Compatibility	G4					↑					↑			✣							3	1
Flexibility	Flexibility	H1					↑					←				↑						2	1

As was said in the beginning, methodologies are blueprints for design processes. Improving or more explicitly optimising these processes is easiest, if the parameters for optimisation are independent. 22 interdependencies have been found, four of which are mutual and the remaining 18 are unidirectional, resulting in 26 unidirectional couples of influencing and influenced requirements. The frequency of a requirement being influenced and being influential is given in the last but one and the last column, respectively. Two requirements are completely independent, five requirements are related to only one other, seven are in relation with between two and four other requirements and five show interdependencies with five or more requirements. These five are Objectivity, Reliability, Comprehensibility, Learnability, and Efficiency.

These results can be interpreted to the effect that the presented set of requirements appears to contain, in general, reasonably independent items. Four groups of comparable size can be distinguished by their level of interdependency. Further assessment of those items highly interdependent and their influence on methodologies should take place, in order to refine the definition by further analysis. It will be interesting to find out whether the statements of Table 2 can be instrumental in identifying key factors of methodologies.

5 CONCLUSION

The objective of the presented research was to define a set of requirements on engineering design methodologies that provides a mean to assess the outcome of the development of methodologies and to compare different methodologies. Interdependencies between the requirements, if existent, have been reasoned and analysed. The requirements have been found to be reasonably independent from each other in general whereas a group of five proved to be prominent by showing, in contrast to the rest, frequent interdependencies with other requirements. These requirements and their relations should be assessed in further analyses. The operationality of this set of requirements has to be evaluated, for example, in a comparative study about existing methodologies.

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Alexander Keller, Hansgeorg Binz
Universitaet Stuttgart
Institute for Engineering Design and Industrial Design (IKTD)
Pfaffenwaldring 9
70569 Stuttgart
Germany
Phone: ++49 (0)711 685-66043
Fax: ++49 (0)711 685-66219
Email: alexander.keller@iktd.uni-stuttgart.de

Alexander Keller is an academic assistant in the institute of Hansgeorg Binz. Keller holds a M.Sc. in Automotive Engineering from Chalmers University of Technology and a Dipl.-Wirtsch.-Ing. in Industrial Engineering from Technische Universitaet Darmstadt. He is researching engineering design methodologies and new types of machine elements under a grant of Deutsche Forschungsgemeinschaft.

Hansgeorg Binz holds an Dipl.-Ing. and Dr.-Ing. in mechanical engineering from Technische Universitaet Darmstadt, working from 1980 until 1985 as an academic assistant at the Institute for Machine-elements and Mechanics. He led several design & development departments in the industry until being appointed to a professorship for engineering design at the University of Stuttgart in 1998.