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ASSESSMENT FRAMEWORK FOR A METHODOLOGY UNDER DEVELOPMENT – APPLICATION TO THE PDA METHODOLOGY

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ABSTRACT

This paper presents an assessment framework for methodologies under development. It is adapted from the evaluation framework for the design of an engineering model developed by Ben Ahmed and colleagues [7]. The assessment framework allows to take into account in a systematic way characteristics (that is, main categories or classes of potential requirements) that are of importance for the assessment of the quality a methodology, beyond effectiveness and efficiency. The framework is intended to be employed similarly to engineering design requirements checklists: ensuring first that no important characteristics are left out; deriving from these characteristics more specific requirements when necessary; using these characteristics or the derived requirements both to drive the development of the methodology and as evaluation criteria to assess the elements of the developed methodology. These characteristics can then be screened again as the methodology is improved. As the methodology is being developed, the assessments can go from wide and qualitative to more stringent. The framework is applied to assess the predictive design analysis (PDA) methodology.

KEYWORDS

Methodology development, methodology evaluation, methodology assessment, evaluation framework, assessment framework, predictive design analysis methodology

1. INTRODUCTION

The definition of a *methodology* adopted here and adapted from [33, p. 66;40, p. 9;46, p. 91] is that a methodology consists of a process model that displays a set of activities and their related methods and tools, often complemented by a set of exemplifications. A *method* is coupled to one or some specific activities of the methodology aiming at achieving a certain goal (see [27, p. 130;33, p. 67;40, p. 9;46, p. 91]. A *tool* (e.g. a CAD system) assists the user in performing his or her activity [33, p. 67].

When methodologies are evaluated, or at least when their assessment is discussed, the characteristic that is almost single-handedly addressed is its effectiveness, that is, how well the methodology leads to the expected results.

This characteristic is undoubtedly important. Obviously a methodology that would not deliver what it promises presents a serious shortcoming. However, there are several other aspects that characterize methodology and that also merit some attention. Some of them have been sometimes mentioned. Efficiency, for example (how well the methodology performs given relative to the amount of time and resources used), or ease of use of the methodology. Although these are subordinated to whether the methodology effectively achieve its goals, they should not be neglected. The primary reason is that these and other aspects can explain the relative low adoption rate of several methodologies in industries. The industry for example favors methods and methodologies that are scalable, informative, and without too rigid procedures [25]. In a recent compilation of studies about the impact of design research on industrial practice [11], the reasons for under-use of methodologies and lack of diffusion are more related to methodology-readiness for application and attractiveness (understanding how the methodology addresses company needs) than to their effectiveness.

Moreover, assessment often occurs in the latter stages of the development of a methodology. This should not be so; the characteristics relevant to a methodology should be specified earlier.

These and other characteristics used for assessment of methodologies have appeared in a fragmentary manner in the literature. A systematic categorization of recurring elements that characterize methodologies is needed in order for the researcher or methodologist (the person developing the methodology) to spot what to focus on, and what to evaluate. Addressing a similar problem, Ben Ahmed and colleagues [7] have devised an evaluation framework for the development of engineering models. This framework has been adjusted for the specification and assessment of methodologies under development.

This publication presents and discusses the foundations of the framework, the framework itself, and an application of the framework to the predictive design analysis (PDA) methodology.

Note on methodologies: In design research, a *methodology* is sometimes defined as the 'science/study of method' [13; see also discussion in 26]. Here the polysemic -logy is employed with the meaning 'collection of (methods)' is used. The *methodologist* is therefore to be understood as the person developing the methodology instead of the scientist scrutinizing methods. Methodologies in this publication can be broad or more specific. Many methodologies are not as broad and as generic as Pahl and Beitz [40]'s; they can fit smaller purposes like the spring development methodology presented in [29] or they can be methodologies adapted for a specific company.

2. THE FRAMEWORK

2.1. The foundations of the framework

Origin and development of the framework

As mentioned above, the framework is adapted from the model evaluation framework of Ben Ahmed et al. [7]. This publication has the same goal with methodology assessment. Ben Ahmed et al. [7]'s framework has been developed to assess engineering models under development in a more systematic way (such as a model for evaluation of car dashboard designs, as presented in their publication). Many of the assessment characteristics presented in [7] can be used directly for methodologies, but some adjustments were necessary. There were also some more theoretical aspects to consider in order to motivate that the transfer of the model evaluation framework to methodology assessment was justified. The details of the motivation and the relations between the two models are presented in the Appendix.

The structure of the framework is based on systems theory (see next section). The principles of systems theory have helped for identifying the different types of requirements, but other literature disciplines were also used. The sources behind Ben Ahmed et al. [7]'s framework can be found among others in [6]. Other sources used to develop the framework are within software requirements engineering (e.g. [28]), knowledge engineering (e.g. [45]), verification and validation literature (e.g. [3]) and by looking at the classification of technical systems properties as well as engineering design requirements checklists [21;27, pp. 108-114;39, pp. 15-20;40, p. 149].

Organization

The focus of the framework is on trying to give a set of generic categories (or classes) of potential requirements, or *characteristics*, a methodology should or could have.

The organization of these characteristics is based on systems theory. Systems theory has been mainly used and developed to model tangible systems, such as natural systems or artificial systems, not the least within the engineering design literature [27;40], but also for non-tangible phenomena [8].

Based on [6;27;31], a simplified description of a system is presented. A system possesses a *structure*, a set of interrelated elements or components. A system interacts with its *environment* (made of other systems) through different *modes of operation (or functioning modes)*. A system has some *finalities* or *purposes* (e.g. surviving or mating, for living organisms). A system experiences *transformations* over its *life cycle* (a technical system can degrade; organisms adapt their structure to their environment)[1]. Finally, in an evolutionary perspective, a system evolves during the course of several generations, and different *versions* appear. A system generally has common characteristics with other systems and can be grouped into a *family of systems* (e.g. species). The system structure is sometimes called the system's *ontology*, the system evolution the system's *genetics*, and its finality the system's *teleology*, terms adopted hereafter.

[1] This is less relevant for methodologies.

Along these different system elements, several characteristics can be described. Similarly to [36, p. 98] the characteristics will be described through following axes: the ontological axis, the functional axis (functioning in interaction with its environment), the genetic axis (evolution of the methodology) and the teleological axis.

Note that this framework does not help determining the overall goal of the methodologies, the functions or the elements (process model, methods, tools) that are necessary to achieve this goal. For example, the framework would not help determining the steps of the process and methods of a methodology for the design of large-scale pumps. But the framework helps assessing *how well the methodology performs*, ensuring that the necessary characteristics beyond *effectiveness* are identified, established and met. This is similar to what is done in software requirements engineering where a difference is made between the functional requirements and the other requirements (functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, portability [28]) or in Hubka and Eder's theory of technical systems where a distinction is made between internal and external properties [27, pp. 109-114].

Use

The framework is intended to be used in a way similar to the engineering design requirement checklists mentioned above. In these checklists, recurring categories (or classes) of potential requirements (material aspects, safety aspects, production aspects, ergonomics, etc.) are listed so that the designer can go through them. These aspects are present in most technical systems but are differently important depending on the specific system to design and its interactions with the environment. The designer would focus on the most important ones first, come back to the other ones later or even ignore some. He or she would use the requirements classes 'as is' first, and then specify them more as the project goes. For example, one could begin by specifying that maintenance is important for the product-to-be and specify the main time between (MTBF) failures later on. He or she would use them both as a requirement for driving the design and as evaluation criteria both during and after designing the system.

The principle is similar for methodology development. The methodologist can go through the different aspects that characterize a methodology, choose to focus on some first and then extend its work to other characteristics later on. For example, not all elements needed for the methodology are known from the beginning, so the *architecture* (organization of the elements of the methodologies) might be neglected first. *Simplicity of use* of the methodology can also be ignored, unless one of the aims of the methodology is to make some concepts more accessible to a certain group of stakeholders.

The methodologist can use these characteristics are general requirements to drive the methodology development. If necessary, the methodologist can develop more specific requirements (with a metric, a target value and means of measurement) that will allow a more thorough assessment.

These characteristics can then be screened again when the methodology is improved.

2.2. The current framework

The characteristics of the framework are presented according to the ontological, functional, genetic and teleological axes.

Regarding the chosen terminology, some of the terms used have different meanings in different fields; it was necessary to make some choices, especially as so many terms were needed.

Ontological axis

The characteristics regarding the structure of the methodology are described Table 1.

Table 1 Assessment of a methodology along the ontological axis

Characteristic and definition
Architecture (structure): extent to which the elements of the body of knowledge are organized, integrated or separated (modularity aspects).
Self-descriptiveness: degree to which the descriptions in the methodology are self-explanatory versus how much is left to the user (use own knowledge or acquire new knowledge). Self-descriptiveness concerns the descriptions of the methods, tools and process of the methodology. Regards also meta-knowledge elements, the knowledge described in the methodology in order to understand it (i.e. the reasoning behind its structure, use, and purpose).
Representation formalism: the form in which knowledge is represented.
Consistency: indication of the level and number of contradictions (low consistency indicates high number of contradictions).
Completeness: indication of the level to which the necessary elements are present.
Independency: refers to the independency of the methodology

from its developer.

Functional axis

As established in [7], three aspects are to be considered for the functional axis: the use of the methodology under normal conditions, the use of the methodology under stressful conditions (regards characteristics of robustness and reliability), and the interactions with the user (regards usability characteristics). The characteristics are described Tables 2, 3 and 4 respectively.

Table 2 Assessment of a methodology along the functional axis – normal conditions of use

Characteristic and definition
Efficiency: how well the methodology provides an appropriate performance, relative to the amount of resources used (time, human resources, etc.), under stated conditions.
Repeatability: how the methodology generates the same results under the same functioning conditions given the same input.
Reproducibility: how the methodology generates the same results under the same functioning conditions given the same input but different users, tools and environment (for example same analysis task with a different analyst, a different software in a different company).
Generality: Breadth of the range of functions the methodology enables to perform.
Interoperability: ability of the methodology to be used with complementary methodologies, or with similar methodologies, or with related processes such as quality assurance (QA) and internal processes of the company.
Replaceability: how the methodology can be used instead of another specified methodology for the same purpose in the same environment.
Compliance: how the methodology complies with standards, conventions, or regulations related to the areas of application of the methodology.

Table 3 Assessment of a methodology along the functional axis – stressfull conditions of use

Characteristic and definition
Robustness: ability of the methodology to operate normally despite large variations in the environments or in the projects.
Error tolerance: ability of the methodology to operate normally despite the presence of erroneous inputs.
Fault tolerance: ability of the methodology to operate normally despite the presence of methodology elements faults.
Error proneness: ability of a model to allow the user to intentionally or unintentionally introduce errors into the methodology or misuse the methodology.
Uncertainty handling: ability of the methodology to take into account the knowledge uncertainties of the user (epistemic uncertainties), that is, whether the user does not know all the elements necessary to perform the recommended actions in the methodology.

Table 4 Assessment of a methodology along the functional axis – interaction with users

Characteristic and definition
Simplicity of use: ease of use of the methodology.
Suitability: how well the model is suitable for a particular task.
Adaptability: how well the model meets contradictory and variable users' constraints and users' needs.
Abstractness: degree to which the model allows to perform only the necessary functions relevant for a particular purpose.
Learnability: degree to which the user learns from the methodology.
Attractiveness: degree of appeal of the methodology for the intended group (independently of the goals of the methodology), e.g. through simplicity or use of established terminology.

Genetic axis

The genetic axis consists of two axes: the taxonomic axis (represents the family of systems) and the phylogenic axis (represents new versions of a system), see e.g. [27]. The genetic axis considers therefore potential evolutions of the methodology and its place within the family of similar methodologies. The first elements regard more the methodology evolution under the control of the methodologist, the last elements regards more a user who is deeply involved in, or responsible, for the methodology. They are presented Table 5.

Table 5 Assessment of a methodology along the genetic axis

Characteristic and definition
Extendibility (or expandability): how easily modifications can be performed to increase the methodology functional capacity.
Maintainability: how easily modifications can be carried out to correct methodology errors.
Testability: how easy it is to test parts of the methodology or the whole methodology.
Position within family: How well it is positioned in relation to other methodologies of the same family.
Implementability: ease with which the methodology can be implemented (decision makers need to accept the methodology, plan for implementation, training).
Flexibility: how easily modifications can be carried out to use the methodology in applications or environments.
Evolutivity: how well the methodology adapts over time to changes in the environment and the user's practices.

Teleological axis

The characteristics regarding how well the goals of the methodology are fulfilled are described Table 6.

Table 6 Assessment of a methodology along the teleological axis

Characteristic and definition
Effectiveness: the ability of the methodology to target all aspects of the goals of a project.
Accuracy: how well the methodology provides the right or agreed results or effects.

3. APPLICATION OF THE ASSESSMENT FRAMEWORK

The framework is applied to a methodology developed for predictive design analysis (called for the sake of simplicity the PDA methodology). The first section describes the methodology's scope and structure. The second section applies the framework to the methodology. The third section reflects on the application.

The methodology has been developed over the last 15 years starting with the establishment of the concept of PDA [9]. The PDA concept has evolved and a supporting PDA methodology has eventually emerged. A first synthesis was published in November 2014 [15] based on a series of prior publications, e.g. [14;18-20;37;41]. This is this synthesis on to which the framework has been applied. The methodology has further evolved since with a second synthesis published in November 2015 [16, Chapter 4], which allows retrospectively to reflect on the role of the framework in the development of a methodology.

3.1. The PDA methodology

Scope

The scope of the methodology is the computer-based design analysis (CBDA) activities, mainly the quantitative analyses of physical phenomena found in mechanical engineering practice that are computationally solvable with computer-aided engineering (CAE) software tools and methods, such as computational structural mechanics (CSM)—mainly finite element method (FEM)—, computational fluid dynamics (CFD) and multibody simulation (MBS). Several methodologies already support CBDA, e.g. [1;2;4;5;12;47]. There is however a greater demand for using CBDA earlier in the engineering design process, shifting from traditional evaluation of product behavior to prediction thereof, hence the term PDA. This in turn leads to an increasing demand for greater confidence in the prediction of established results.

The PDA methodology is defined as "a specific computer-based design analysis methodology that supports the systematic handling of uncertainties and errors during the computer-based design analysis activity throughout the development of the artifact" [15].

Elements from the PDA methodology have been utilized by the second author of this publication and colleagues in industrial practice at the engineering consultancy company Validus Engineering AB. This has allowed both for controlling some aspects of the methodology and for further developing it. Not all elements of the PDA methodology are utilized in all projects, simply due to the diverse nature and characteristics of the various projects performed. About 50 such projects are performed annually. Several projects have been published [17;32;42;43].

Structure

The methodology contains the following elements, see Figure 1.

1. Methods for handling aleatory uncertainties and epistemic uncertainties[2]
2. Process model with inclusion of both types of uncertainties
3. Specific processes
4. Supporting process (quality assurance, or QA, activities, progress monitoring, traceability)
5. Documentation of acquired knowledge

1. Methods for handling uncertainties. Sources of uncertainties to the design analysis activity are identified and grouped along their levels of influence on the activity, see Figure 1. For epistemic uncertainties, a guideline is proposed; for aleatory uncertainties a synthesis of recommended methods from the literature dealing with random, or stochastic, processes, is presented.

2. Process model. The PDA process model is formulated in general terms so that it can be adapted to majority of product development processes utilized in industry. It consists in the three main activities of analysis task clarification, analysis task

[2] *Aleatory uncertainty* is used to describe the inherent variation associated with a physical system or product and also with the measuring devices utilized to monitor it. *Epistemic uncertainty* (from *episteme*, knowledge) is used to describe the possible lack of information or knowledge that is derived from some level of ignorance of the system or environment or in any activities and phases involved in performing the modeling and analysis or simulation [38].

execution and analysis task completion, and their corresponding steps, see Figure 2.

3. Specific processes. The PDA process model presented above gives some general guidance for planning and executing the design analysis task, and for communicating results. However, it is not always obvious how an adaption of this general model for specific design analysis tasks should be handled. To that end, a few specific process models have been developed in order to facilitate this transformation: a) for explorative analysis activities, b) for evaluation and verification analysis activities, c) for physical testing supporting activities, and d) for method development activities.

4. Supporting processes.

QA activities: the QA activities consist of self-checks and planned quality check (QC) activities with the purpose of revealing and capturing any deficiencies connected with both intentional and unintentional errors.

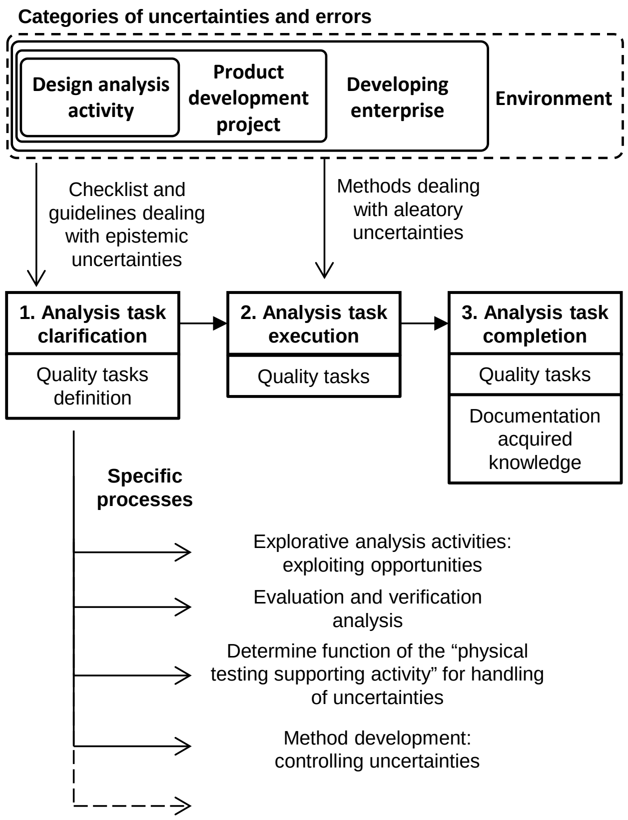

Figure 1 Outline of the PDA methodology.

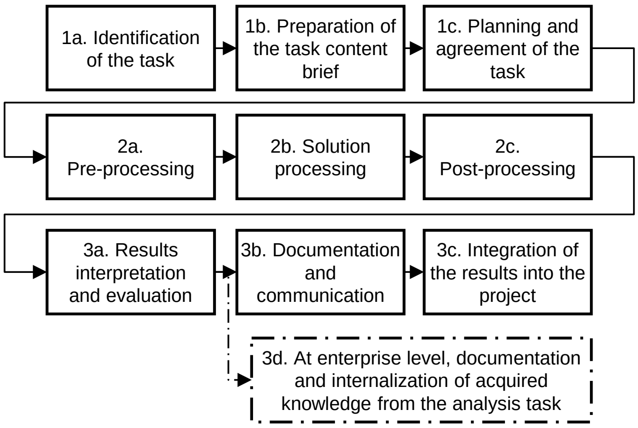

Figure 2 Overall design analysis process model with defined activities and steps.

Progress monitoring: through status and progress reporting activities on the ongoing work.

Traceability: All models, data and information established during the execution of the activity should be gathered in some form of tracking system that could either be in the form of engineering data management (EDM) or based on a file system approach.

5. Documentation of acquired knowledge. Experiences gained and lessons learned should be developed into best practice procedures. Using this knowledge in future design analysis tasks will increase confidence in predictions.

3.2. Assessment of the PDA methodology

This assessment of the PDA methodology as published in [15] is reported according to the use of the assessment framework (see Subsection Use in Section 2.2). That is, for each characteristic of the framework, three points are reported: 1) It is reported whether the characteristic was considered at the onset of the development of the methodology, and if so, what needed to be considered more specifically to drive the methodology development forward; 2) The result of the methodology development is assessed; 3) Action plans are decided to further develop the methodology, if necessary.

The PDA methodology has been assessed separately by two persons. The differences were then discussed and a synthesis was then devised. The synthesis is reported in Tables 7-12.

Table 7 Assessment the PDA methodology along the ontological axis

Characteristic and definition	*Assessment*
Architecture (structure): extent to which the elements of the body of knowledge are organized, integrated or separated (modularity aspects).	1. A starting point has been that the methodology should be organized around the classical activities of pre-processing, execution, post-processing [4;5;12;47], extended with a planning phase and with an appropriate communication of the results to the engineering designer. 2. There is a clear separation over the process and the methods used. The goal for each method is clear and they can be used (or not used) independently of each other. The articulation of these methods is less clear (some are 'support processes', the documentation part hangs lose)—a consistency problem. 3. Re-articulate the methods.
Self-descriptiveness: degree to which the descriptions in the methodology are self-explanatory versus how much is left to the user. Regards also meta-knowledge elements.	1. The user should have good knowledge of design analysis. The methodology should help the user determine which other specific methods and tools are necessary (e.g. design of experiment, traceability tools). 2. This has been respected. Novel elements of the methodology are well described e.g. factors [19]. Others are methods well developed by others, and referred to. Less references for knowledge management, traceability, etc. 3. Improve the descriptions of e.g. knowledge management.
Representation formalism: the form in which knowledge is represented.	1. The methodology is supposed to be used at an operational level. The language is that of design analysts. 2. This has been respected. 3. Continue this way.
Consistency: indication of the level and number of contradictions (low consistency indicates high number of contradictions).	1. This characteristic was not prioritized. *Completeness* (all necessary elements should be present) was prioritized over *consistency*. 2. Need to re-organize the methods and role of the factors in a more consistent way. 3. See 2. Focus especially on the support processes.
Completeness: indication of the level to which the necessary elements are present.	1. Important that the analyst is given access to all types of methods necessary to ensure confidence. 2. Continuous control that this is the case through literature reviews and project. 3. More refined method for predictability assessment activity needed.
Independency: refers to the independency of the methodology from its developer.	1. Not prioritized. 2. The methodology might reflect the methodologist's background and experiences (analysis of complex systems such as off-shore industry, airplane industry, etc.). Even if some elements of the methodology have been introduced by and discussed with colleagues (e.g. traceability), the methodology is the product of a sole author. 3. Should be assessed in the future.

Table 8 Assessment the PDA methodology along the functional axis – normal conditions of use

Characteristic and definition	*Assessment*
Efficiency: how well the methodology provides an appropriate performance, relative to the amount of resources used (time, human resources, etc.), under stated conditions.	1. This is one of the implicit consequences of the purpose of the methodology. By "supporting the systematic handling of uncertainties and errors" of not only the analysis task's input but the whole task, the recommended activities for planning for the appropriate amount of resources used (time, human resources, etc.) should increase performance. 2. Beyond the strong focus on planning [41], the continuous monitoring [18] ensures that resources are adapted. Moreover the methodology gives the user a holistic perspective that should help him or her being efficient. 3. It would be valuable to validate parts of this aspect, or to try to find a way to test it.
Repeatability: how the methodology generates the same results under the same functioning conditions given the same input.	1. Implicit goal. 2. With recommendations to develop guidelines and lessons learned in place describing the process and methodologies should ascertain repeatability. 3. No specific action plan. As for efficiency, very difficult to test.
Reproducibility: how the methodology generates the same results under the same functioning conditions given the same	1. Not prioritized. The methodology has been used by colleagues of the author but in the same company.

input but different users, tools and environment.	2. With guidelines and lessons learned in place describing the process and methodologies should ascertain reproducibility. 3. Should be assessed in the future
Generality: Breadth of the range of functions the methodology enables to perform.	1. The goal has been that the methodology should fit most analysis tasks, at least CSM analyses, on a par with, e.g., [2;4]. 2. Parts of methodology are tested with about 50 projects a year. 3. The methodology should be tested in more CFD and MBS analysis tasks.
Interoperability: ability of the methodology to be used with complementary methodologies, or with similar methodologies, or with related processes such as QA and internal processes of the company.	1. A buit-in goal has been to integrate design analysis into the engineering design process. The methodology also borrows elements from other methodologies, which should ease interoperability with those. 2. Focus on support processes has led to integration with QA. 3. Continue on the integration with the engineering design process. Test integration with internal processes in a company.
Replaceability: how the methodology can be used instead of another specified methodology for the same purpose in the same environment.	1. Not prioritized. 2. Because the methodology focuses on interaction/integration to engineering design, the integration of the new methodology should be easier. 3. Investigate which elements would be missing, how to present the methodology in comparison to other design analysis methodologies.
Compliance: how the methodology complies with standards, conventions, or regulations related to the areas of application of the methodology.	1. It is one of the goals. 2. The method is quite compliant (tested in areas where regulations are heavy). 3. Continue this way.

Table 9 Assessment the PDA methodology along the functional axis – stressfull conditions of use*

Characteristic and definition	***Assessment***
Robustness: ability of the methodology to operate normally despite large variations in the environments or in the projects	1. Not given high focus. 2. The 4 different processes should ensure that the user plans efficiently even for widely different tasks. 3. Should be controlled.
Error tolerance: ability of the methodology to operate normally despite the presence of erroneous inputs.	1. Prioritized. 2. Errors and uncertainties handling are in the heart of the methodology. 3. Continue the development of methods and tools (need to update the currently presented uncertainty handling methods in [14]).
Fault tolerance: ability of the methodology to operate normally despite the methodology elements faults.	1. Not taken into account: as the methodology is still used internally, if faults are discovered, the methodology is modified. 2, 3. see 1.
Error proneness: ability of a model to allow the user to intentionally or unintentionally introduce errors into the methodology or misuse the methodology.	1. See *error tolerance.* 2. The guidelines [19], QCs [18] and the validation method [18] are handling this aspect. Beyond error handling directly related to analysis, other methods also help mitigate errors, e.g. traceability: if for instance a resource leaves the project or company the monitoring, traceability should allow for continuation with another resource. 3. No action plan.
Uncertainty handling: ability of the methodology to take into account the knowledge uncertainties of the user (epistemic uncertainties), that is, whether the user does not know all the elements necessary to perform the recommended actions in the methodology.	1. See *error tolerances*. 2. See *error tolerances*. The identification of the factors that can affect the design analysis task and the guideline proposed to deal with them [19] are actions that deal specifically with that. 3. Further handling of these uncertainties is planned.

*The methodology has been developed specifically for supporting design analysis activities in handling uncertainties and errors. Therefore the methodology performs well on these characteristics.

Table 10 Assessment the PDA methodology along the functional axis – interaction with users

Characteristic and definition	***Assessment***
Simplicity of use: ease of use of the methodology.	1. Make the methodology operational. 2. The methodology presents concrete descriptions of how to do it, less theory about what is presented and why. 3. Should be tested with users not coupled with the authors.
Suitability: how well the model is suitable for a particular task.	1. Should be particularly suitable to CSM analyses. 2. Has worked well with the tested projects. 3. Suitability to other areas should be tested.
Adaptability: how well the model meets contradictory and variable users' constraints and users' needs.	1. At the heart of the methodology. 2. Part of this methodology has been developed to resolve contradictions with the different needs of the different users. It stresses the necessity to have a common understanding of the needs of the engineering designer and the analyst as well as the constraints the environment. 3. No specific action planned.
Abstractness: degree to which the model allows to perform only the necessary functions relevant for a particular purpose.	1. Partly prioritized. 2. The planning part gives the possibility to include/exclude various elements of the methodology. The 4 specific processes help to design a specific process for the company. But at the detailed level there is only limited guidance for choosing or excluding parts of the methodology 3. Look into it.
Learnability: degree to which the user learns from the methodology.	1. A goal is to explain the importance of handling uncertainties and errors, and how to perform an analysis in those conditions. 2. The synthesis tries to be pedagogical in that sense. 3. As this is an academic project, the material could be learning material for future engineers.
Attractiveness: degree of appeal of the methodology for the intended group (independently of the goals of the methodology), e.g. through simplicity or use of established terminology.	1. The goal is that the methodology appeals to analysts in industry. 2. The methodology has been presented in various conferences where industrials have expressed their interest. 3. The methodology needs further development before addressing this particular aspect more in depth.

Table 11 Assessment the PDA methodology along the genetic axis

Characteristic and definition	***Assessment***
Extendibility (or expandability): how easily modifications can be performed to increase the methodology functional capacity.	1. This aspect has not been considered. 2. New elements have been added on the methodology during the years. It has often been hard to incorporate them in a consistent way (cf. *consistency*). 3. The methodology should be made more consistent in order to allow modifications.
Maintainability: how easily modifications can be carried out to correct methodology errors.	1. Not prioritized. 2. Some modifications are easily done, others more difficult. This is again related to the consistency of the methodology. 3. This can become an issue when the methodology is available to more industrials. New versions and errors have to be communicated. The methodology must be further developed and enter a stable state prior to further release.
Testability: how easy it is to test parts of the methodology or the whole methodology.	1. Not prioritized. Parts of the methodology are used routinely. 2. Parts of the methodology are used often and are well-known. It is much more difficult to assess the whole methodology as its outcomes depend on the nature of the project. 3. No clear action plan on this aspect.
How well it is positioned in relation to other methodologies of the same family.	1. No clear goal on this aspect. 2. The positioning of this methodology towards other methodologies is not clarified. 3. It would be interesting 1) to investigate the integration of design analysis process models in the engineering design process at the companies—this integration is quite absent from the literature [37]; 2) to discuss this methodology to authors of design analysis

	literature.
Implementability: ease with which the methodology can be implemented (decision makers need to accept the methodology, plan for implementation, training).	1. Not a specific goal. 2. The methodology itself gives some guidance so as to choose which parts to implement, but there is no guideline supporting implementation. 3. Should definitely be a future action.
Flexibility: how easily modifications can be carried out to use the methodology in applications or environments.	1. The methodology should easily be used in different projects. 2. The 4 specific processes give a great insight in how to use the methodology for different types of analysis tasks. The continuous monitoring helps get inputs from 'outside' and take actions [18]. 3. No specific action planned.
Evolutivity: how well the methodology adapts over time to changes in the environment and the user's practices.	1. This has not been considered in an orderly manner but the addition of new elements under the years shows that it has been considered. 2. The evolution of the method testifies of it. The author and colleagues' regular use of the methodology in different areas leads to natural adaptations. However for potential users from outside, the adaptations might be less evident. The 4 specific processes help in that direction though. 3. No particular action plan for now.

Table 12 Assessment the PDA methodology along the teleological axis

Characteristic and definition	***Assessment***
Effectiveness: the ability of the methodology to target all aspects of the goals of a project.	1. Implicit goal for almost all methodologies. It has not been given focus in all areas of the methodology though. 2. The focus on planning helps increasing the chances to be effective. 3. No plan at the moment. Maybe more focus on the confidence level of the prediction during planning. As for all methodologies, very difficult to assess.
Accuracy: how well the methodology provides the right or agreed results or effects.	1. The goal is that the methodology should facilitate the establishment of the expected accuracy as well as means to achieve it (uncertainty handling gives a level of accuracy in the prediction). 2. The methodology presents the process, methods and activities to achieve just that. 3. No plan at the moment.

3.3. Further developments

As mentioned above, the PDA methodology has been further developed since then, see [16]. This allows some feedback regarding the assessment framework.

Some action plans have been followed. For example, works on the *architecture* and *consistency* of the methodology have been achieved: methods for handling uncertainties, the supporting processes and documentation have been grouped into a set of methods called confidence appraisal activities (CAAs), which makes the methodology also clearer. It has also been noticed that there will be a limit between *consistency* and *ease of use*. Some methods that the methodology has integrated, such as verification and validation (V&V), are widely used and even if they are contradictory with some other aspects of the methodology they cannot be altered. Inconsistencies will therefore remain in the methodology.

Other plans have been postponed. Regarding the *independency* characteristic, the methodology has not been used outside a close circle of colleagues.

New elements have been added. In fact, the methodology's scope has shifted from focusing on uncertainties in the prediction to increasing confidence in the prediction, of which uncertainties is a part [16]. A predictability assessment activity is now included, as one of the CAAs. The four specific models have now been replaced by examples of how to use the methodology in specific contexts. This simplifies the methodology and is therefore supposed to improve its *simplicity of use* and *learnability*, without decreasing its *suitability*. Other improvements are also due to the discussions following the presentation of the method in diverse conferences.

4. DISCUSSION AND CONCLUSION

The assessment framework allows the methodologist to have a broad overview over the methodology under development. It is important to emphasize that not all characteristics need an expressed attention and that many can be assessed qualitatively. But even a quick assessment could prevent or eliminate flaws that could otherwise cause difficulties later on in further development or use.

On the other side, some characteristics might need to be assessed thoroughly, like *efficiency* and *effectiveness*, to not mention them. In that case, specific requirements derived from the presented characteristics (that is metric, target values and mean for measurement) should be identified and established in order to allow for a more quantitative assessment. Here another issue arises that it is important to consider while using this framework. It is very difficult to assess thoroughly a methodology, whatever the criteria. The problem lies in the nature of a methodology: 1) a methodology has a broad scope and it is difficult to cover it in a satisfactory manner—the PDA methodology aims at covering most types of design analyses; mechanical engineering design methodologies aim at covering the design of all tangible products. 2) A methodology is a support: it might increase the chances of a successful outcome but it cannot guarantee it. Too many other parameters come into play. 3) It is also difficult to assess whether the success of the outcome is due to the methodology, the user or some other element of the environment. 4) The industry and individual users adopt what they need, not necessarily a complete methodology; it is in those cases difficult to extrapolate the degree of contribution of the methodology to industrial applications. An ersatz of validation for a criterion (validation of a methodology is often linked with effectiveness but it should be linked with any criterion of relevance) must be achieved by proxy, discussion or other manners. Such evaluation attempts have been made in the past, sometimes successfully, sometimes inconclusively [34, Chapter 4;35].

From the above definition of methodologies, it can be seen that the difference between methodology and method is not straightforward. Some methods like the morphological matrix or TRIZ have been extended with other methods so that they can almost be considered as methodologies. The extent to which the presented framework can be used for method development will be considered in future work.

A difficulty in applying the framework is to differentiate between the different axes because they interact. For example, the level of *self-descriptiveness* is linked to the *simplicity of use*. It is also necessary to have a balance between *abstractness* and *completeness* (if too abstract difficult to apply, if too detailed, difficult to apply in different fields). It might be therefore important to consider inter-characteristics relationships [7]. Overall, it is now necessary to consolidate further the framework by extending the review of other assessments frameworks and by using the evaluation framework on other methodologies and with external, independent researchers. There is also room for improvement (for example *attractiveness* is relatively broad), and will always be possibility for further development—as are other assessment framework such as in software requirements engineering, see e.g. [10, pp. 58-59]. But it is believed that the bases of the assessment framework are now established.

Finally, the original framework [7] separated knowledge evaluation from model evaluation, see the Appendix (the knowledge evaluated being the knowledge produced by the model, e.g. design analysis results). As discussed in the Appendix, there is a beginning of support for asserting that these two evaluation types could and should be merged. Developing and improving such a unified framework, would require multi-disciplinary work but this would be a contribution to knowledge assessment in general.

APPENDIX: MOTIVATION FOR THE ADOPTION AND MODIFICATIONS OF THE MODEL EVALUATION FRAMEWORK

As mentioned above, this appendix clarifies the links with the framework of Ben Ahmed at al. [7] and motivates the needs for changes. The reasoning is not as obvious as it seems and it contributes indirectly but importantly to the results presented in this publication. Therefore the whole Appendix is dedicated to it.

A.1 Motivation

More on knowledge

A certain vision of knowledge is necessary to understand Ben Ahmed et al.'s framework.

The concept of knowledge is an entire field of science in itself (epistemology) and is debated in most scientific disciplines. Any attempt of definition can be disproved by another definition, see e.g. the debate on the data-information-knowledge-wisdom (DIKW) hierarchy [22;44] within the information science field. For consistency, the vision of knowledge synthesized by Ben Ahmed [6] which follows a systemic view is given here: ontologically, knowledge is represented by signs having a certain meaning in a certain context depending on the knowledge owner (this somehow also includes the more positivistic view where knowledge can be seen as invariant in meaning and context – in that case the definition still holds if one considers that there is one meaning and one context); teleologically, knowledge is sufficiently organized so that it can be used to achieve a goal, that is, for understanding a phenomenon or for some course of action (e.g. to solve problems); functionally, external factors trigger related declarative and procedural knowledge helping to understand a phenomenon or solve a task; finally bodies of knowledge relates to other bodies of knowledge, and knowledge evolves (genetic axis).

This definition also acknowledges that knowledge can be modeled with systems theory. It is also important to note that with that definition a piece of information does not need necessarily to be validated in a strict sense to become knowledge, it is enough that knowledge believed to be adequate by its user, or at least hypothetically adequate.

More on the evaluation framework for the design of an engineering model

The evaluation framework by Ben Ahmed et al. [7] is introduced for the case of engineering models. A model is defined teleologically in this context as “a tool to develop a goal-dependent knowledge” [7, p. 109], that is, the model is not an end in itself but a means used to derive knowledge that can be used, say, in a development project.

The purpose of the framework is thus to assess both whether the model is adequate for the knowledge to generate and whether knowledge generated itself is adequate, see Figure 3. There also two sets of criteria.

15 knowledge evaluation criteria are proposed to assess the adequacy (and thus acceptance) of the generated knowledge, mainly based on Heylighen [23;24]. The criteria are categorized as *objective criteria* (e.g. to which degree the generated knowledge is invariant over modalities, time and individuals), *subjective criteria* (e.g. to which degree the generated knowledge is useful to the user), and *intersubjective criteria* (related to acceptance by a group of individuals).

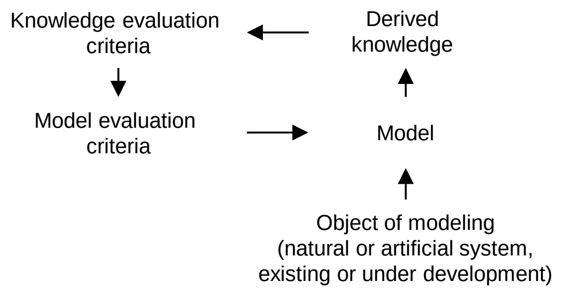

Figure 3 Knowledge evaluation and model evaluation [7]

The model evaluation criteria consist in 28 or so criteria that are structured along the ontological, functional, genetic and teleological axis, as are the current methodology assessment criteria.

More on model and modeling

A model used to generate knowledge is knowledge itself. A model can indeed be considered ontologically as a specific arrangement of chunks of knowledge. In other cases than engineering models (and even in some cases, engineering models themselves), models are not only used for generating extraneous knowledge as output; the arrangement of knowledge itself is a new knowledge, helping for example to understand the modeled phenomenon. This is one of the common functions of a model, see e.g. [30]. The model is an end in itself, even if it can evolve indefinitely.

If the resulting model is the piece of knowledge one is interested in, both the model and the knowledge embedded in the model should be assessed.

The methodology case

As defined in the introduction, a methodology in general consists of a process model that displays a set of activities and their related methods, techniques and tools. This is the ontological definition. A methodology has of course a purpose. For an engineering design methodology, the aim is often to support the designer developing the documentation of the product-to-be that satisfies a set of requirements. The PDA methodology supports the systematic handling of uncertainties and errors during computer-based design analysis. A methodology is therefore a gathering (or body) of knowledge arranged in a certain way to help users producing specific knowledge (e.g. a product documentation or the behavior of a product). It can be considered a model, or a meta-model (a model of model) if the methodology needs to be derived into a more specific action plan for the user, which is often the case.

But a methodology in itself also presents new and valuable knowledge to the user. The user learns more about engineering design or design analysis by reading the methodology. Methodology therefore has two goals: to support the user in whatever course of action he or she intends to perform, and to give him or her better understanding about the process and related areas. Using the methodology is not the only end. Therefore, the methodology is a model in the larger sense described in the preceding section.

Should methodology be assessed separately as a model for generating knowledge (with the knowledge assessment criteria) and as knowledge for generating models/action plans (with the model assessment criteria)? (Notwithstanding the assessment of knowledge created by the use of the methodology or action plan, that is, the documented product or the analysis result.) This should not be the case because there is a large overlap between both assessments. The knowledge embedded in the methodology is the knowledge of the process and methods to use, that is, assessing knowledge in the methodology corresponds mainly to assessing the elements assessed with the model evaluation criteria… The two should therefore be merged.

Merging knowledge and model evaluation criteria

When one looks at the criteria for model evaluation in [7], one notices that many knowledge evaluation criteria can be assimilated with model evaluation criteria. For example, the objective criteria of *invariance* can be assimilated with the criteria of the functional axis (normal and stressful conditions, see Tables 3 and 4). The subjective *simplicity* criterion can be integrated into the *usability* criterion (now changed into *simplicity of use* in the current domain). This correspondence between criteria is not coincidental as similar properties are necessary for a model (which is a body of knowledge) to work properly and for a piece of knowledge to be adequate.

Based on this reasoning the framework of methodology assessment, presented Section 2.2, has been developed.

In the case where a methodology would only be used as a model to generate adequate knowledge and not be itself knowledge in the eye of the user, would the modified framework still be valid? Yes, because the user of the methodology assessment framework can choose not to include some criteria.

A unified evaluation framework?

The modified framework is to be used for evaluating a methodology. Knowledge produced through the use of a methodology (product-to-be, etc.) still needs to be evaluated as well. The overall knowledge evaluation criteria can still be used to that end.

But as mentioned above, one knows also that knowledge or a body of knowledge can be modeled following systems theory: a body of knowledge has a structure (arrangement), a purpose, etc. Knowledge evaluation criteria could evaluate this knowledge along to the ontological, functional, genetic and teleological axes. Therefore, many of the criteria used specifically for the methodology assessment could also be used for knowledge assessment in general (at least in the studied engineering domains). In that case, only one framework would be necessary (the framework would be used twice, one for the model/methodology and one for the produced outcomes). Preliminary results support that claim but much more work is required to support it.

A.2 Relations between both models

This section presents the relations between the original evaluation framework and the methodology evaluation framework.

Table 13 presents the connections between the two frameworks in a more detailed manner.

Note that some specific new criteria have also been added, such as those related to implementation. Also, a methodology does not only interact with its user but also with different elements of its environment: the company, the project, the persons to which the produced knowledge will profit, etc.

Most criteria relative to knowledge evaluation are also indicated in the table. There are a few exceptions: the criteria *invariance over modalities*, *invariance over time*, *invariance over persons*, are related with the criteria along the functional axis (normal and stressful conditions) and therefore not mentioned. The criteria *individual utility* and *collective utility* are related to the individual and

Table 13 Relations between the model and knowledge evaluation framework and the methodology assessment framework

Methodology assessment framework	***Model and knowledge evaluation framework***
Ontological axis	
Architecture	Partly: *Reusability* (in functional axis). In the original framework, the focus was on the use aspect of modularity. Here modularity is considered as intrinsic to the ontology of the system. *Distinctiveness* (objective knowledge evaluation criterion).
Self-descriptiveness	*Self-descriptiveness.* *Distinctiveness* (objective knowledge evaluation criterion), *Expressivity* (intersubjective knowledge evaluation criterion).
Representation formalism	Was part of *self-descriptiveness.* *Expressivity* (intersubjective knowledge evaluation criterion).
Consistency	*Consistency.* *Consistency* is also subjective knowledge evaluation criterion
Completeness	Changed from *incompleteness.*
Independency	*Independency.* *Invariance over persons* (subjective knowledge evaluation criterion).
Functional axis	
Normal conditions	
Efficiency	*Efficiency* (teleological axis). Moved here because it is more related to the functional axis.
Repeatability	*Repeatability.*
Reproducibility	*Was partially included in repeatability*
Generality	*Generality.*
Interoperability	*Interoperability*. This criterion was adapted for methodology.
Replaceability	*Replaceability.*
Compliance	*Usability compliance*. Extended compliance to other domains than just usability.
Stressful conditions	
Robustness	Originally *controllability*. *Controllability* is also an objective knowledge evaluation criterion.
Error tolerance.	*Error tolerance.*
Error proneness	*Error proneness.*
Fault tolerance	*Fault tolerance.*
Uncertainty handling	New.
User interaction	
Simplicity of use	Changed from *usability* (too broad a term). Includes also *operability.* No need to separate the preparation for input, etc. from operation and control. *Simplicity* (subjective knowledge evaluation criterion).
Suitability	Changed from *understandability* but meaning is similar.
Adaptability	Adaptability.
Abstractness	Abstractness.
Learnability	*Learnabilty*, but different meanings. In the original framework, was related to the model ability to learn.
Attractiveness	*Attractiveness.* *Novelty* (subjective knowledge evaluation criterion), *publicity*, *authority*, *conformity* (intersubjective knowledge evaluation criteria).
Genetic axis	
Extendibility	*Extendibility.*
Maintainability	*Maintainability.*
Testability	*Testability*. Originally related to how easily modifications can be performed within the validation stage of the complete model under construction. The validation part has been relaxed.
Position within family	New.
Implementability	New.
Flexibility	*Flexibility*. Modified slightly, was too specific.
Evolutivity	New.
Teleological axis	
Effectiveness	*Effectiveness.*
Accuracy	*Accuracy/precision.*

collective preferences. Persons will favor methodologies that help them satisfying their goals. Depending on the different goals of the different persons, different criteria will have different weights. In other words, all criteria can be involved. Therefore, *individual utility* and *collective utility* are not mentioned either in the table.

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