

EVALUATION OF DATA QUALITY IN THE CONTEXT OF CONTINUOUS PRODUCT VALIDATION THROUGHOUT THE DEVELOPMENT PROCESS

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ABSTRACT

Focus of current research activities is to develop a holistic and capable method for the continuous validation of product properties throughout the development process by the means of simulations to significantly reduce development cycles and to increase product quality.

Simulation methodology is an appropriate device to gain knowledge about real systems through models. However, it will be absolutely necessary to indicate which input data the simulation results are based on in order to prevent systematic errors and avoid implying a precision that does not exist. Data quality must be pre-defined depending on the current process step if simulations are to be executed efficiently. Therefore, the objective must be to be able to describe the available data basis and to give methodical support to assist engineers in the decision-making process as far as necessary. Consequently more goal-oriented iteration loops can be carried out resp. the further working process can be suitably designed in terms of concurrent engineering. This paper shows mandatory basic considerations concerning a method to evaluate data quality at hand.

Keywords: data quality, simulation planning, product validation

1 INTRODUCTION

Continuous validation of product functionality must be ensured throughout the development process. In addition, in terms of cost and time savings, an early and simultaneous validation of product functionality by the means of simulations is to seek. It is still an open question which simulations can be executed at what point in time to really support product development processes in terms of concurrent engineering and to reduce the development risk by purposeful and early validation of product functionality [1]: Data certainty and data availability simulations are based on are a major problem. This set of problems can be assigned to all steps of the whole development process.

This shows that it is absolutely necessary to consider aspects of organization and optimization of data flows to develop capable methods for simulation planning. With a view to the manifold and heterogeneous data sources and data consumers within interdisciplinary product development efficient data and information flows have to be ensured. These have to be consequently checked and modified with respect to changing requirements. Only that way a high information quality, as the essential basic requirement for efficient process flows, can be provided. The evaluation of information quality is the essential prerequisite concerning efficient information quality management (induce resource decisions, set goals, measure success) [2], [3].

2 RELEVANCE OF DATA QUALITY IN THE CONTEXT OF SIMULATIONS

In order to efficiently execute simulations a pre-defined data quality regarding both completeness and certainty is required. This is closely connected to the progress of the process and valid for data concerning the level of development to be verified as well as reference criteria needed for validation.

A previously detailed planning of simulations is neither possible nor wise. Thus, it may be necessary to modify e.g. solution principles during the development progress that entail executions of simulations again. Especially in the stage of domain-specific concretization decisions to leave out or add property validations are possible. Therefore, the available data basis is closely connected to the course of the process, which is on the one hand affecting the structuring of the product description and on the other hand providing information which simulations are to be applied sensibly and provide useful results. Similarly, the simultaneous development of components has to be mentioned as an influencing factor. Herewith, boundaries of subsystems are determined and various process interfaces

are consequently constituted. The simulation quality concerning the validation of system integration is largely depending on the supply of information from different subsystem developments. If simulations are to be employed reasonably, comparison criteria must be defined in order to verify simulation results. Customer requirements as well as Design for X (DFX) criteria are available as starting points, but these are often vague demands (e.g. "safety"). Translating them into concretely measurable or rateable parameters is difficult as they may be interpreted very differently depending on the developers' state of knowledge. Particularly in the early stages of a development project, a lot of assumptions have to be made because data are simply not available [1]; working with assumptions is not unusual and certainly legitimate, since it is generally based on the wide experience of engineers. In this context it is to be checked to what extent these experiences can be included in the evaluation of the data quality of reference criteria. However, a lot of reference criteria result only from the concretization of the solution. In this context it needs to be clarified which granularity of the concretization of a solution is required for property validation. An approach to this is deduced from the information flow during the development process.

As shown above a lot of data and information occur in the course of the development project. This leads to the fact that development steps have to be repeated due to new insights and changed basic conditions. Therefore, the real simulation procedure in fact can only be formulated explicitly when looking at the latest results of analysis and the progress in development in order to ensure goal-oriented continuous functional validation throughout the development process at any time. The importance of data quality in the context of simulations and its influence on an efficient product development is displayed by an impact model (Figure 1): the combination of "+" and "-" at the ends of a connexion shows how the attribute at one end impacts the attribute at the other end.

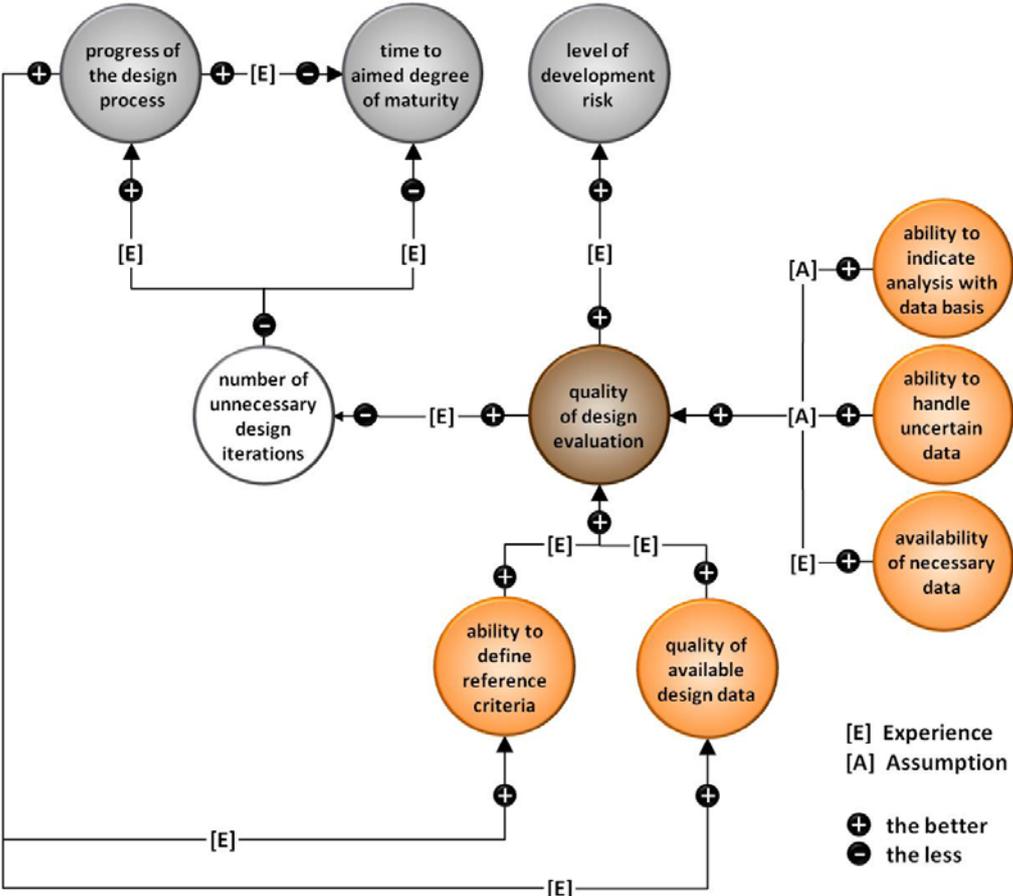


Figure 1: Impact of data quality on the virtual product validation

Basically, there are two factors that have a significant influence on the quality of a design evaluation: available data basis and an adequate support for decision-making that is associated with it. On the one hand the availability resp. the release status of updated design data and reference criteria is closely connected to the course of the process and fundamentally relevant. As mentioned before, reference

criteria can be vague demands. Generally, their concretion is task resp. result of the early stages of a development process in order to provide more detailed reference criteria. The concrete design of a product and therewith the determination of characteristics which contribute to the fulfilment of the reference properties can be comparably considered - here, a concretion from system design to the determination and domain-specific design of specific physical principles can be noticed as well. The quality of simulation results and therefore, the obviousness of a simulation is highly depending on the fulfilment of data requirements ("uncertainty" and "completeness" exemplarily mentioned concerning available data). Based on this it is also important to make it possible to consider the data quality virtual product validation is based on resp. the degree of fulfilment of the data requirements when evaluating simulation results.

Therefore, the objective must be to be able to describe the available data basis and to give methodical support to assist engineers at the decision-making process as far as necessary. Consequently more goal-oriented iteration loops can be carried out resp. the further working process can be suitably designed. Manifold methods and tools for virtual product validation are already existing, but it is still an open question which simulations can be executed at what point in time to really support product development processes resp. whether they are actually goal-oriented executable (with respect to available data) and deliver useful results [1]. This lack of knowledge focuses on the question whether the available data basis is adequate and reliable. In many cases this uncertainty leads to the fact that simulations are executed relatively late in the development process and that leads to a late detection of errors in turn.

Previous explanations clarify that the quality of simulation results and therefore, the obviousness of a simulation is highly depending on available data. Simulation results have to be marked with respect to the data basis they are based on in any case in order to avoid systematic errors and avoid implying a precision that does not exist [1]. Finally, an efficient provision and preparation of data is required to get an efficient product validation by simulation. In addition, the development risk can be reduced by the purposeful planning and integration of simulations and an early validation of product functionality.

3 TERMINOLOGY

Discussions concerning the term "data quality" in qualitative experts' interviews revealed that in practice, compared to ample scientific literature, a limited spectrum of conceptual dimensions prevails and data quality is equalized by most of the respondents with correct data [4]. Empiric analyses by [5] show that this understanding does not meet the complexity of "data quality", however [4]. Furthermore, note that the term data quality may have different meanings depending on previous knowledge/intention of the users (context of use) [4]. This shows that the context of use has profound influence on the evaluation of available data. This is not only limited to the user's knowledge, which data are important for ones context of use, but also implicates the characteristic and its influence on the results of one's use. In order to create a conceptual understanding the term data quality will in the following be defined and then (Chap. 4) detailed in the context of virtual product validation.

3.1 Data

According to [6] data are objective facts which are not interpretable without further context, and thus, to be understood as raw material. Only when they can be put in context, categorized, calculated and corrected, they represent in terms of structured data with assigned relevance and clear purpose realizable information. This is absolutely necessary so that they can be used as a meaningful basis for decision since interlinked information (in terms of knowledge) support referencing and comparisons. This context illustrates that data have to be always available in sufficient quantity and quality to direct development processes target-oriented. This stresses the strategic meaning of a data basis to be used. Data and product are in tight mutual relation and represent the essential work base in the development process. The work base' potential of success is to be exploited with efficient tools and processes [7].

In addition, in the context of a simulation planning it is necessary to develop strategies for the validation of data quality and the handling of insecure data. A classification of data necessary for the specific simulations can be operated in dependence of the process progression. The basis for the characterization of the data quality is the process progression and with it the resulting release status for product data which needs to be defined by an appropriate metric. Please note that the below presented approach of [5] to measure information quality uses the term data interchangeably with the term

information, since in practice manager intuitively differentiate by describing information as data that have been processed.

3.2 Data quality

A widely used approach to define data quality relates to the qualification of data to fulfil certain usage. It is, thus, described as "data that are fit for use by data consumers" [5]. According to [8] data quality is the fitness of data for all purposes that require it. These definitions are comparable to the quality connotation of [9] in which quality is defined as the "entirety of characteristics (and values of characteristics) of a unit according to its ability to fulfil determined and preconditioned requirements". Determined requirements as well as the fulfilment of these demands are, therefore, decisive for the evaluation of given data quality. These definitions emphasize the multi-dimensionality of the term "data quality", but do not sufficiently recognize the temporal context of use which needs particular attention in the dynamic and highly iterative product development process since data availability is tightly connected to the process step. [10] defines data quality as a "multi-dimensional measure for the ability of data in order to fulfil their purpose connected to its recording/generation. This ability can change over time when requirements change.". This predication also stresses the relevance of the requirements put on the data at a certain point of time. Without a doubt this may be interpreted as an indirect link to concrete process steps and herewith connected a specific context of use (e.g. data requirements for concrete computer-aided tools) in the product development process. In general data are of high quality if they fulfil the requirements set by the user.

As mentioned before, the requirements for data quality are to be understood as a multi-dimensional construct. Table 1 shows the differentiation of attributes according to [5], the founders of Total Data Quality Management (TDQM): each of these dimensions is a crucial success factor for the functioning of an information system and serves as the quality evaluation of an information product. Information products can be considered as the information output from an information manufacturing system and have value transferable to the consumer. With regard to the virtual product development characteristics serve, as a result of the synthesis step, as input for the analysis process – therefore, CAD systems in which characteristics are primarily determined and filed, can be seen as an information manufacturing system for the simulation validation in the analysis step.

Table 1: Attributes of data quality [5]

Category	Attribute	The extent to which...
Intrinsic Information Quality (IIQ)	Believability	...data is regarded as true and credible
	Accuracy	...data is correct and reliable for the task at hand
	Objectivity	...data is unbiased, unprejudiced, and impartial
	Reputation	...data is highly regarded in terms of its source or content
Contextual Information Quality (CIQ)	Value-added	...data is beneficial and provides advantages from its use
	Relevancy	...data is applicable and helpful for the task at hand
	Timeliness	...data is sufficiently up-to-date for the task at hand
	Completeness	...data is not missing and is of sufficient breadth and depth for the task at hand
	Amount of data	...the volume of data is appropriate for the task at hand
Representational Information Quality (RIQ)	Interpretability	...data is appropriate languages, symbols, and units, and the definitions are clear
	Ease of understanding	...data is available without ambiguity and easily comprehended
	Consistent representation	...data is presented in the same format
	Concise representation	...data is compactly represented
Accessibility Information Quality (AIQ)	Accessibility	...data is available, or easily and quickly retrievable
	Access security	...the access to data can be restricted and controlled

The 4 main categories of the information quality IIQ (the fact that information has quality in its own right), CIQ (requirement that information quality must be considered with the context of the task at hand), AIQ and RIQ (both emphasize the importance of the role of information systems) can be detailed in 15 quality dimensions all together. This was chosen by statistic methods from over 100 potential attributes to describe information quality. Starting point for this was a study that identified dimensions of the term "data quality" by a two-stage survey [5]. This differentiation is one of the most quoted concepts to describe and validate information quality [3], [4]. Further attributing approaches depending on the application of data quality exist (e.g. [10], [11], [12], [13], [14],...). Based on the shown concept of [5] an evaluation concerning particular data attributes in the context of a continuous validation of product properties throughout the development process is made within chapter 4.1.

3.3 Data quality management

More and more companies consider the improvement and warranty of data resp. information quality to be of high importance and therefore, as an elementary keystone within system integration projects [3]: especially with respect to processes based on heterogeneous data sources and data stakeholders high information quality is valued to be the basic requirement to achieve efficient operative activities. With respect to the development of mechatronic products it is important to keep in mind that, based on different points of view on the product (and therewith related differences concerning data requirements and data content itself), the variety of used tools in the context of domain specific development processes and highly manifold interfaces within the process flow special attention must be given to the information exchange.

[15] developed the Total Quality Management Cycle (TDQM) by combining Deming Cycle (iterative problem-solving process: Plan - Do - Check - Act) and information manufacturing (Figure 2). TDQM points out that the information management and quality awareness associated with it on the one hand has to be holistically and systematically considered and on the other hand must be proactively included in the organization and processes of a company.

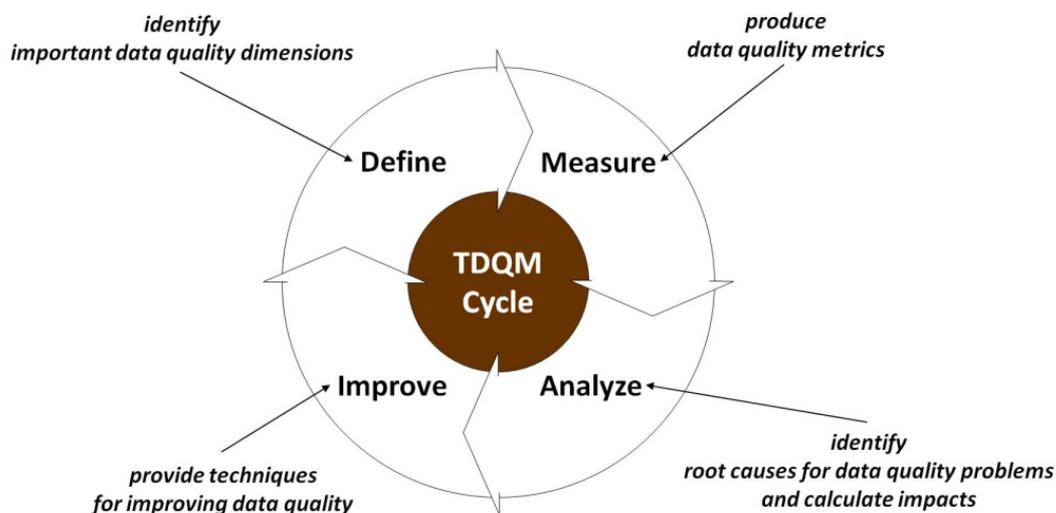


Figure 2: TDQM Cycle [15]

The philosophy of the TDQM cycle is included in the evaluations of data quality in the context of product validation within the development as well, but it occurs slightly modified (Figure 3): detailed considerations concerning meaningful quality dimensions (Chapter 4.1) are followed by explanations about the relevance of sensitivity analysis in order to analyze the significance of manifold tool depending input parameters (cf. Chapter 4.2 in conjunction with Chapter 4.3). That is important to be able to describe mathematically the situational simulation quality at hand resp. to assign a "final score" (Chapter 4.3). Hence, the achieved simulation quality is more tangible and no longer an exclusive hypothetical construct based on assumptions concerning input quality. Consequently the step "analyze" of TDQM is replaced by the interpretation of simulation quality (decisions concerning the following process progress are based on that) resp. its intention is included in the sensitivity analysis that is previous to the step "measure".

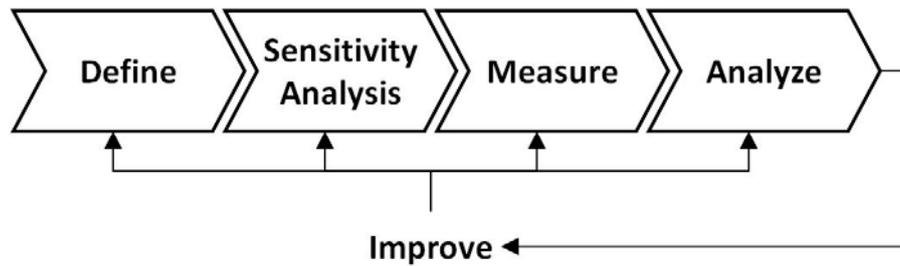


Figure 3: Data quality management in the context of simulations

The last step "Improve" will not be considered at the context at hand, but the sensitivity analysis logically supports to strengthen a proactive handling of data quality as well.

4 IDENTIFICATION OF DATA QUALITY IN THE CONTEXT OF SIMULATIONS

4.1 Essential attributes to identify data quality

Attention should be paid to the fact that all quality attributes shown before do not exist independently but are closely connected [4], [16]: exemplary different sources with redundant and differing data lead to doubtful believability, as data consumers only know that data is conflicting, but do not know the source to which quality problems should be attributed. This often causes a low additional value of the data and consequently to a disuse. Information about the causes of mismatching data leads to a poor reputation of less accurate sources. Therefore, these data sources are viewed as having little added value and consequently are less used as a data basis because of the common poor reputation.

As mentioned before the quality attributes according to [5] are one of the most cited concepts to describe and estimate information quality. Single quality attributes are of different importance, show different linkages among each other or are placed within different hierarchies depending on the focus of use - comparable with the execution of simulations.

When executing simulations required parameters for different simulation methods are a priori determined and just differ depending on the used simulation method or tool. For this reason the category RIQ can be considered as almost insignificant as parameters are always available in an interpretable form and language because of their numerical value. Consequently concise representation as well as comprehensibility is ensured. A concise representation of data can be assumed as well if standard computer-aided design and simulation systems resp. standard data formats are used. Believability, reputation and objectivity as attributes for intrinsic data quality can be classified as less relevant with respect to the same background. However, it is necessary to mention the fact that these attributes depend on subjective impacts (e.g. data generation and management based on a construction engineer's specific competence). This mainly applies to the objectivity of assumptions that have to be made during the development process. Accuracy stands for the most important attribute of intrinsic data quality - the extent to which data is considered as correct and reliable for the task at hand has to be included in the estimation system. At this juncture considerations concerning objectivity (mainly) as well as believability and reputation can also be included. The dimension accuracy is in specific relation to the contextual data quality as the context of use and herewith linked specific data requirements are focused. It has to be noted that the previously low rated attributes may not be totally disregarded. Thus, e.g. it is to investigate whether RIQ is completely fulfilled at every time or special attention must be given to its attributes, in spite of used standard tools and data formats, as they crucially influence data quality. In general it must be ensured that construction engineers and simulation engineers have the same understanding and consider the background of data requirements of each other at any time. Especially with respect to alternating teambuilding, new employees or similar these quality dimensions have to be checked as they constitute necessary boundary conditions that have to be satisfied.

Certainly contextual data quality can be considered as the core element within a rating system, but not all attributes have an immediate impact. The extent is obsolete to which data is beneficial, provides advantages from its use (value-added), is applicable, and helpful for the task at hand (relevancy) as the choice of a simulation method or tool determines required parameter with respect to amount and type and hence, a priori, the "contents design" of both attributes is determined as well. Herewith the

dimensions "completeness" and "appropriate amount of data" are closely connected - these can be precisely evaluated by a comparison of the determined parameter requirements and the available data basis (see Chapter 4.3). Here, the timeliness of used data can be considered as well. Obviously the process state has a high influence on the meaningfulness of executed product validations at hand. The usage of outdated data seems to be reasonable only at the time when no updated data are available and therefore, data from past and comparable development projects can be used.

In addition, on the lines of [3] access security is no longer considered as an original dimension as this attribute does not describe aspects that cannot be expressed with respect to the user's perspective by other dimensions (e.g. accessibility). The degree of accessibility (data is available, or easily and quickly retrievable) has to be considered as an essential quality attribute and is closely connected to the timeliness of used data. The interplay of CAx-systems within the process chain is affected by an intensive exchange of information and data preparation. An updated study concerning the cooperation between construction and calculation shows that significant potential exists to optimize the supply of relevant data information [17]. This assessment is consistently confirmed in the context of current industrial projects. In that case a proactive data management must influence communication structures and processes in particular.

A selection of relevant dimensions is illustrated by Figure 4. In the following chapter some of these attributes will be used to directly estimate the quality of simulation output.

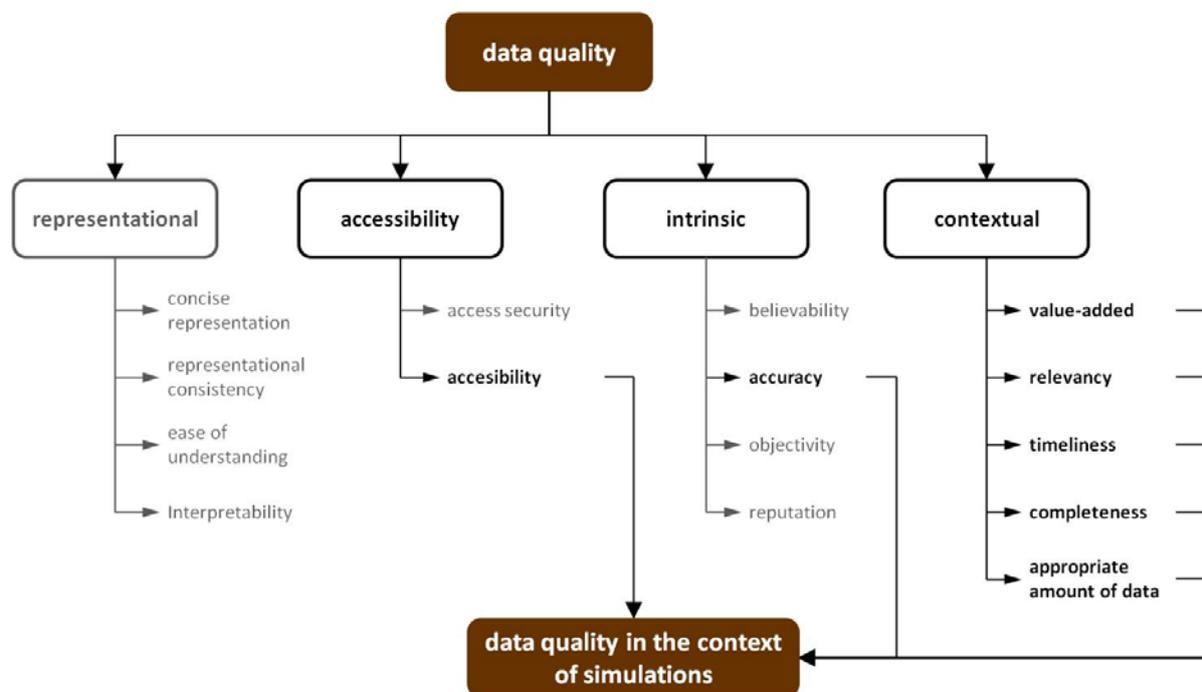


Figure 4: Quality dimensions in the context of simulations

4.2 Sensitivity analysis of required input data

The sensitivity analysis is the study of the relationships between information flowing in and out of a model [18]. Here, the parameter sensitivity of an output is identified whereat both qualitative and quantitative conclusions are possible.

The simulation methods and tools used within the product development are based on the mathematical modelling of the technical system to be analysed. Such mathematical models are defined by a series of input parameters, connections among these and a specific output. The input of a mathematical model is subjected to many sources of uncertainty as well as errors of measurement, absence of information and poor understanding of the driving mechanism - sensitivity analysis was originally created to deal simply with these kinds of uncertainties [18]. A sensitivity analysis has two major impacts. On the one hand the trust in the model and its predictions is increased by providing a better understanding of how the model output depends on changing input [18]. In addition this evaluation increases the sensitizing within the product development: data providers as well as data consumers become more aware of the relevance of data to be provided resp. the utilization of a certain data quality. Thus, an analysis of the

parameter sensitivity of the modelling that is used can help to raise data quality as all individuals that are involved in product development are being motivated to deal proactively with generated data. Sensitivity analysis provide an opportunity to evaluate results of virtual product validations with respect to the underlying data basis and finally substantially support to keep the provided data quality in mind.

Monte Carlo Simulations (e.g. used in MATLAB) provide an excellent method to study the sensitivity of a result concerning changes in the assumptions resp. to evaluate the sensitivity of model results concerning uncertain input data. Similarly, neural networks or genetic algorithms can be used.

4.3 Identification of output quality of simulations

As mentioned before simulations are based on mathematical models, consequently required input parameters and simulation output can be accurately specified and connected. The output quality is mainly influenced by two factors: on the one hand the relevance of a specific input parameter resp. its impact on the simulation result and on the other hand the influence of a parameter variation within a specific range of values. The latter can be optimally analysed by sensitivity analysis and included into decision support. The relevance of a specific parameter depends on the objective of a simulation and determined by the basic interrelation between input and output. Both effects can be summarised by a single weighting factor (e.g. expressed by a percentage) and be considered within the summarisation of impacts of several parameters (summation of weightings = 1). Afterwards the identification of available data quality of required parameters has to be questioned. Generally simulations require more than one single input parameter. At the time when one parameter is missing the data requirements are not completely fulfilled (quality criterion "completeness"), but an appropriate amount of input data (quality criterion "amount of data") can be available to get meaningful simulations within the current process step. The lack of one parameter (no matter if based on unavailable accessibility or data just have not been generated) can be taken into account by assigning the data quality "0" and that way the quality of a simulation result is depending on the weighting of the lacking parameter. Available and therefore, usable parameter are not necessarily rated via the value "1" - available data quality at hand that is related to the release status has to be integrated. Here, e.g. estimations concerning the timeliness as well as the processing state can be considered. These are done by construction or simulation engineers and the range of values is]0;1]. Their expert opinion based on knowledge about quality criteria and experience with former development projects ensures an impartial analysis and estimation. The abundance of experience shall be deemed to be the legitimisation for assumptions concerning still missing parameters and therewith consequent parameter quality. Finally the estimation of output quality (range of value [0;1]) can be done by a simple summation of all input qualities weighted with associated relevance of parameters (Figure 5).

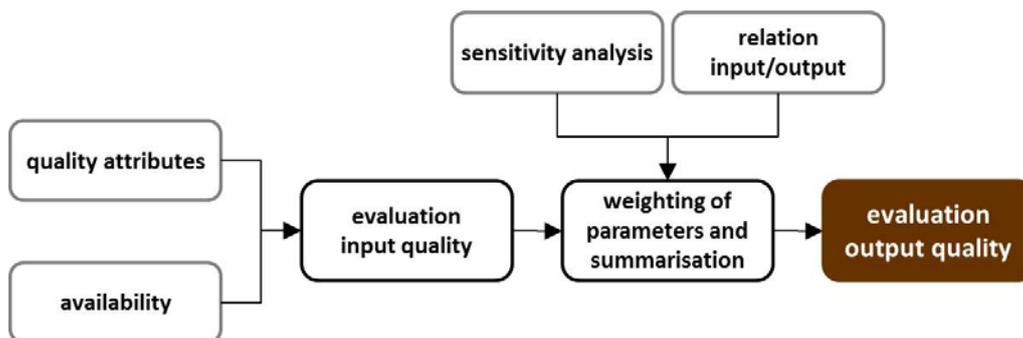


Figure 5: Evaluation system of data quality in the context of simulations

The design of a concrete evaluation system to summarise data qualities of various input parameters in order to form a final value and to consequently characterise a simulation output by a quality evaluation is not reasonable at present. Upcoming research activities that focus input analysis (sensitivity analysis) of concrete simulation tools in the context of specific simulation examples will surely disclose advanced and more detailed ways to design a sustainable evaluation system. The objective is to provide a mathematical system to identify a final value of output quality resp. to enable its classification by a striking scheme (three broad categories seem sensible). This system can be used as decision support as well as sensitizing concerning data quality. It is important to consider transparency

and reproducibility. Beside the analysis of specific simulation examples it is goal-oriented to carry out a survey amongst calculation specialists to note their requirements for decision support and to be able to consider their experience and requirements concerning data quality in the context of virtual product validation (an industry partner for this purpose is already found). Finally this survey supports to identify reasonable quality criteria and to ensure practicability of the aimed decision support. In particular, the independence of used quality attributes must be ensured to provide an adequate evaluation system. [4] noted that not all quality attributes according to [5] exist independently. For this purpose, a solution must be worked out (e.g. aggregation of similar attributes to a new and / or higher-ranking attribute).

Previous explanations with respect to terminology, quality criteria and evaluation of simulation output can be seen as mandatory basic considerations to go on upcoming research in a systematic and focused way. According to [8] an understanding of all intended purposes for that data is needed to evaluate data quality.

5 SUMMARY

Iterations during the product development are unavoidable. In terms of virtual product development goals resp. direction of iteration loops are highly depending on simulation results that are substantially influenced by the underlying data basis in turn. This line of reasoning must be continued: a very detailed resp. final simulation planning in the phase before the development is neither possible nor wise. Mechanisms are rather required which trigger simulations depending on the input data available [1]: necessary data must be provided at an adequate level of certainty to get meaningful simulation results. Therefore, only the necessary types of simulations are specified with respect to the required product properties - the actual point in time when they will be carried out must depend on the data release. Both data release and predications with respect to data quality have to be linked to the process model to raise effectiveness and efficiency during the development of interdisciplinary technical systems.

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