First Step Towards the Technical Quality Concept for Integrative Computational Design and Construction

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Abstract. In a world with a growing population, the development of new construction forms is becoming increasingly important. This development has to be accompanied by intense quality assessment. Within the framework of the Excellence Cluster IntCDC (Integrative Computational Design and Construction for Architecture) of the German Research Foundation (DFG) at the University of Stuttgart, a Holistic Quality Model for building systems is to be developed. This model should consider social, environmental as well as technical aspects and thus enable a holistic quality assessment of the building. For the technical part of the model quality parameters and characteristics for many different disciplines like architecture, structural engineering, engineering geodesy, mechanical engineering and system engineering should be included. This definition of the critical parameters will take place in close alignment with the co-design-based development of building systems. In addition, the construction processes are modelled in order to allow quality propagation through the construction process. This contribution will deal with a first quality concept, a first quality model as well as exemplary quality characteristics and parameters gathered from concrete and timber constructions. Exemplary quality propagation possibilities will be highlighted based on previous work at the Institute of Engineering Geodesy (IIGS). The quality will be evaluated at different decision points during the building processes in the future.

Keywords: Quality model · Quality assurance · Quality concept · Quality parameter · Quality characteristic · Tolerance

1 Introduction

Nowadays, the development of new building forms is important in order to meet the global demand for buildings. Within the framework of the Cluster of Excellence for Integrative Computational Design and Construction for Architecture (IntCDC), funded by the German Research Foundation (DFG) at the University of Stuttgart, new buildings are to be constructed to fulfill current social, environmental and technical requirements.

The aim of the IntCDC project is to develop new innovations in the building sector by using the full potential of digital technologies [1]. Here the development of a

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comprehensive methodology of the “co-design” of methods, processes and systems is in the focus [2, 3]. For this new and innovative processes and methods also, quality assurance is important. Within the overall project, a Research Project with the name “Holistic quality model for IntCDC building systems: social, environmental and technical characteristics” was developed to rate the new buildings systems and processes. This holistic quality model will be developed within the framework of the overall project in cooperation with the Institute for Social Sciences (SOWI) and the Institute for Acoustics and Building Physics (IABP) and the Institute of Engineering Geodesy (IIGS) in order to represent the social, environmental and technical characteristics and parameters.

In Fig. 1 the planned holistic quality model is shown. Here, the subject-specific models are each represented by exemplary quality characteristics, since the final characteristics and parameters used are developed in the course of the project [4, 5]. The final quality characteristics and parameters will be developed within the project in close interdisciplinary cooperation. The quality requirements in the construction process vary greatly depending on the used material and construction method. These requirements differ also according to discipline and are implemented in a co-design-based development process.

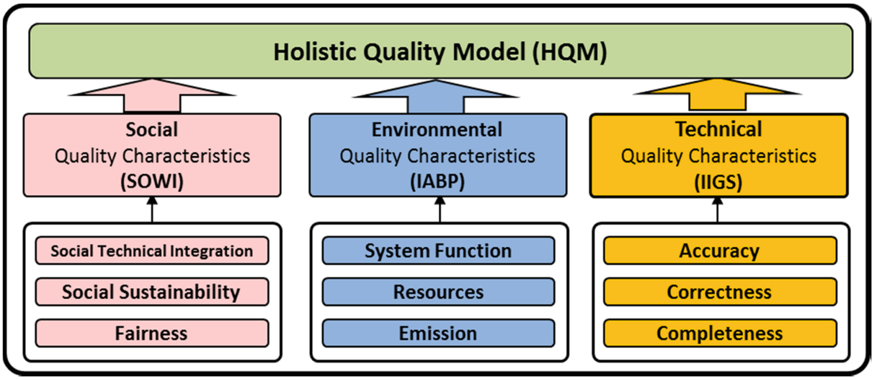

Fig. 1. Holistic quality model for IntCDC building systems [6]

Another difference compared to the previous evaluation of construction processes is that this is not a linear evaluation process. Rather, quality feedback should be provided to the disciplines involved as early as possible in order to be able to identify any problems and to initiate appropriate countermeasures, which in turn are then subject to a quality assessment.

In the context of this work, first the basic concepts of quality and their relation to previous work in the context of quality assessment will be discussed. Also general quality terms such as quality characteristics, parameters and the specific parameter tolerance correctness are defined. Then a first concept is explained regarding the identified quality characteristics and parameters. Finally, previous methods of quality propagation, which will be further developed with the project, are explained. A distinction between the propagation of the statistic quantities and the propagation of the tolerances is made.

2 General Quality Terms and Models

2.1 Overview of Technical Quality Models

The term quality is defined according to DIN EN ISO 9000 as "degree to which a set of inherent characteristics fulfils the requirements" [7]. Here the requirements are defined as "need or expectation that is stated, generally implied or obligatory" [7]. Quality assurance therefore refers to ensuring that the requirements for a product or process are fulfilled.

In general, a quality model is used to assess the quality of products and processes based on quality characteristics and parameters. Figure 2 shows the structure of a quality model.

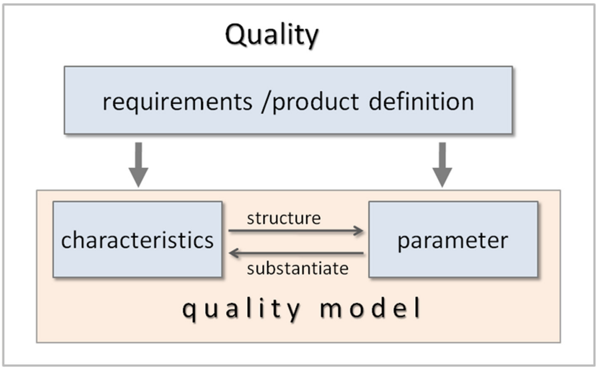

Fig. 2. Definition of a quality model [8]

The assessment and evaluation of the quality of a product or a process is of great importance in many areas of daily life. For this reason, quality models are application-orientated in various disciplines. In the field of software development, they are used for the evaluation of a developed software product. In [9] the prototype of a quality model, which evaluates a new software by means of quality characteristics such as correctness, efficiency, reliability or functionality, was developed. The qualitative aspects of software products were also considered in [10]. Here different software packages for adjustment calculation were examined. The application of quality models has also been used in the field of geodesy for a long time. As an example, quality modelling is applied to geodetic networks. For these networks, the quality characteristics accuracy and reliability are of great importance. For engineering geodetic networks, the characteristics sensitivity and separability are also used for the evaluation [11]. Quality modelling is also already being used in the construction sector. For example, within the framework of the EU project QuCon "Development of a Real Time Quality Support System for the Houses Construction Industry", a real-time quality control system has been developed for the use in housing construction processes [12]. Quality assessment also plays a role in the development of Building Information Modelling (BIM). For this purpose, a BIM based construction quality management model was developed, that does not base on characteristics and parameters, but takes into account data from the design to the construction of a building [13].

2.2 Quality Characteristics and Parameters

When setting up quality models, a differentiation must be made between quality characteristics and quality parameters. A quality characteristic describes a specific characteristic of a product or process. In DIN EN ISO 9000 the quality characteristic is therefore defined as "inherent characteristic of a product, process or system related to a requirement" [7]. These quality characteristics can now be substantiated by quality parameters. Each parameter can be quantified by a (measured) value. In addition, it should be mentioned, that a quality characteristic might have one or more quality parameters.

From [8] quality characteristics and parameters for engineering geodetic processes in building construction were extracted. As an example, these quality characteristics and parameter are presented in Table 1. Here a distinction is made between product-related and process-related quality characteristics. One of these quality parameters, the tolerance correctness, will be further described below.

Table 1. Quality characteristics and–parameters for engineering geodesy processes [8]

Quality characteristic	Parameter	Product- (pt)/process-related (ps)
Accuracy	Standard deviation	pt
Correctness	Topological correctness Tolerance correctness	pt pt
Completeness	Number of missing elements Number of odd elements	pt pt
Reliability	Condition density Minimal detectable error Vulnerability to failure	pt pt ps
Timeliness	Time delay	ps

2.3 Tolerance Correctness

The tolerance T of a building component is kept when the difference between the actual size S_{act} and the given nominal size S_{nom} is less than the difference between the maximum possible component size and the minimum possible component size. In the following, this tolerance is assumed symmetrical. This dependency is given by

$$\frac{T}{2} \geq |\mathrm{S}_{\mathrm{act}} - \mathrm{S}_{\mathrm{nom}}| = \tilde{d}, \tag{1}$$

with $\tilde{d}$ as actual deviation. The real size is determined by measurements. However, the measured quantity S_{meas} is not identical with the actual size as they differ by the uncertainties of the measuring device. This is normally not taken into account if the keeping of the tolerances is assumed [14]. In order to be able to evaluate compliance with the tolerance under consideration of the measurement uncertainty, the term tolerance correctness is introduced [8]. For this purpose, the standard deviation σ of the measurement is first converted into the measurement tolerance T_M. The measurement tolerance T_M is given by

$$T_M = 2 \cdot k \cdot \sigma. \tag{2}$$

Here k is a factor which depends on the error probability α, e.g. $k \approx 2$ for $\alpha = 5\%$ and assumed Gaussian distribution. This measurement tolerance decreases the construction tolerance T_C, since the tolerance

$$T = \sqrt{T_M^2 + T_C^2}. \tag{3}$$

Since these two tolerances are statistically independent of each other, the quadratic propagation has to be applied. Thus, Eq. (1) results in

$$\frac{1}{2}\sqrt{T^2 - T_M^2} \geq |S_{\text{meas}} - \text{S}_{\text{nom}}| = d, \tag{4}$$

with d as random deviation. The tolerance correctness T_k now indicates whether the required tolerance was met or not. The tolerance is met if

$$T_k = \left(\frac{1}{2}\sqrt{T^2 - T_M^2}\right) - d \geq 0. \tag{5}$$

3 Technical Quality Model Within the Framework of IntCDC

3.1 Technical Quality Concept for IntCDC

The quality requirements of the different disciplines within the framework of IntCDC differ widely. Therefore, a survey was first conducted to determine the various quality characteristics as well as the standards and regulations applicable to the various disciplines. The first results of this survey concerning the general understanding of quality and the different quality requirements for the development stages of the individual construction and planning phases are presented. It shows that the relevance of technical quality modelling is of high importance for all disciplines. Furthermore, it was shown that a large part of the participants orientates their work on national and international norms and standards. In addition, urban development guidelines play a major role, especially in the planning phase. From this, a technical quality model is to be created, which will evaluate the individual requirements at various previously defined checkpoints [12]. The technical quality concept includes a first set-up of the quality model, as well as the corresponding quality characteristics and parameters.

In a first step, product related quality characteristics are extracted from the commonly used standards [15–18]. As it turns out the characteristics themselves do not differ much between the different materials used and disciplines involved, but the parameters surely differ. Here, the component properties in concrete construction and in timber construction were considered first. In addition to geometrical parameters, which must be known with a specified tolerance, the characteristics that describe the stress properties of the material are of major importance. This is for example the bearing capacity. Furthermore, characteristics such as compliance with fire protection regulations or with water permeability of walls must also be considered. The evaluation of the quality characteristics and parameters shows a multi-levelness of the parameters. Some primary parameters are combined to determine high-level condensed parameters.

3.2 Exemplary Quality Characteristics and Parameters

In the following, some quality characteristics are presented for concrete and timber building components. As already mentioned, in addition to the quality characteristics used in geodesy, characteristics such as bearing capacity, usability, strength, durability or fire protection properties are of high importance. In Table 2 some exemplary quality characteristics and parameters for the technical quality concept are shown.

Table 2. Exemplary quality characteristics and parameters for the technical quality concept for IntCDC for concrete and timber building components

Quality characteristic	Exemplary parameters
Accuracy	Standard deviation
Correctness	Tolerance correctness
Completeness	Number of missing elements Number of odd elements
Bearing capacity	Load application time Pressure, tension
Water permeability	Stress class

In the first step, special attention will be paid to the geometric parameters. These include, for example, tolerances for dimensions, angels, flatness or deviations from alignment [15]. When considering the tolerances of the dimensions, it must also be taken into account whether these are dimensions or clear dimensions. It must also be noted that the tolerances are given in relation to the size of the component.

3.3 Condensed Parameters and Primary Parameters

As already mentioned, quality characteristics are structured by several quality parameters. In this structure, a quality characteristic can have several condensed quality parameters, which in turn consist of several primary parameters. The values of the condensed parameters may be based on the values of the primary parameters. It should also be considered that a primary parameter could be assigned to several condensed parameters. This structure is shown exemplarily in Fig. 3. Here the water permeability of a building component is described by the stress class as well as the utilization class. These correspond here to the condensed parameters. The parameter stress class in turn contains the parameters granulate size and wall thickness. These correspond to the primary parameters.

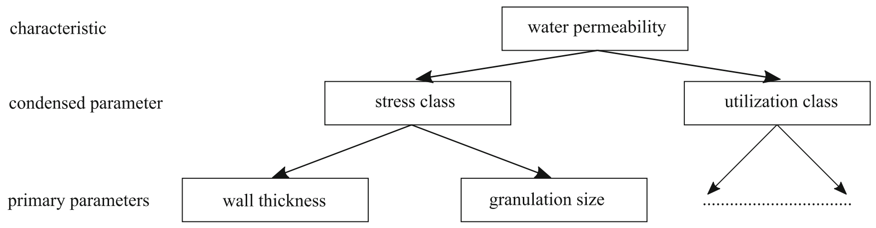

Fig. 3. Concept of use of characteristics, condensed-parameters and primary parameters

4 Quality Propagation Possibilities

4.1 Accuracy and Correctness Propagation

In order to be able to make an early statement about the quality of the final product (in this case the finished building, or an individual part of the building process), the quality characteristics and parameters must be propagated through the process. At this stage, it is not possible to discuss quality propagation for all parameters, since they are not defined up to now. However, as investigated in other projects (e.g. [19]), the propagation of quality accuracies and the propagation of tolerances plays an important role. Therefore, the propagation of the tolerance correctness should be mentioned. Regarding the tolerance correctness, it should be noted that the tolerance correctness is not propagated by the process, but the tolerance T and the measurement tolerance T_M, which are used for the calculation according to (5), have to be propagated.

4.2 Quality Propagation for Measurements

In order to be able to carry out quality propagation for statistic quantities e.g. measurements, classical variance-covariance propagation can be applied, or alternatively a Monte-Carlo simulation can be performed. This is of importance, since in many cases the size, angle and flatness cannot be measured directly, but is a function of measured values. For example, the determined component length is a function of the measured distances and angles. In classical variance-covariance propagation, the input variables are assumed to be normally distributed. Furthermore, linear dependencies between measured variable and target variable are assumed. A linearization is necessary for this [11]. In contrast, Monte Carlo simulation offers the advantage that analytical or numerical differentiation for linearization is not necessary. In addition, the input variables here do not have to be normally distributed. Instead, they can follow any distribution. However, m random numbers for the measured variable must first be generated with the assumed distribution function. The expected value, the variance or confidence intervals can then be derived by evaluating the model several times. The general procedure for both methods of propagation is shown in Fig. 4. The disadvantage of the Monte Carlo simulation compared to variance covariance propagation is that a higher computational effort is required due to the m-times calculation, exemplarily 100 000 times, and thus the computing capacity influences the duration of the solution [19]. In principle Guide to the Expression of Uncertainty in Measurement (GUM) [20, 21], that is widely applicable e.g. in mechanical engineering, purpose the use of Monte-Carlo too.

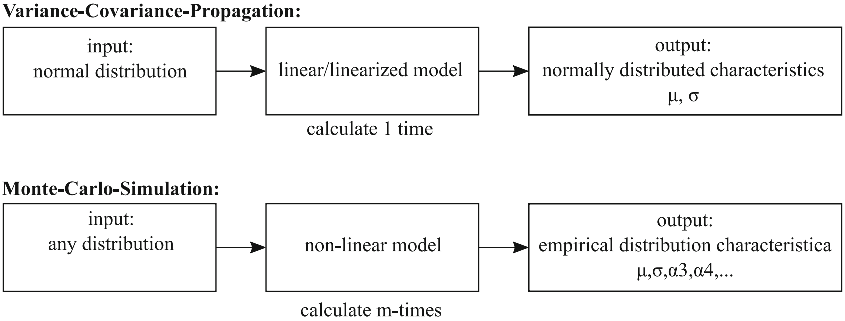

Fig. 4. Comparison of variance-covariance reproduction and Monte Carlo simulation according to [19]

4.3 Quality Propagation for Tolerances

Besides the variance-covariance propagation of the measurements, sometimes the tolerances have also to be propagated through the construction process. Different fit calculations are used for this [22]. On the one hand, values of all individual tolerances may be added up. This results in the total tolerance T_{comb} by

$$T_{\text{comb}} = \sum T_i, \tag{6}$$

where T_i are the included tolerances. This corresponds to a linear tolerance propagation, which is mainly consider in mechanical propagation processes. If a component consists of four individual building components, each has a certain tolerance. If these parts are assembled to form a common building system, the tolerances have to be summed up. On the other hand, as in geodesy, fit calculations are carried out under considering of the tolerance propagation. This results in the total construction tolerance following

$$T_{\text{comb}} = \sqrt{\sum (T_i)^2}. \tag{7}$$

This method is popularly used in civil engineering as well as engineering geodesy. The decision among (6) and (7) is also a challenge for the future.

For the tolerance correctness, the tolerance T can be propagated according to 4.3, the measurement tolerance T_M can be propagated according to 4.2 and the random deviation d can be measured.

5 Conclusion and Outlook

In conclusion, it is shown that the first quality characteristics have been identified and structured. In comparison to other quality models, condensed quality parameters and primary quality parameters are introduced. In the further progress of the project, the individual characteristics and parameters will be structured and related to each other. In addition, the quality characteristics and parameters must be extended from the component level to the manufacturing processes and the whole building systems in order to be able to carry out a quality assessment of these processes. The processes are also needed to create quality propagation methods through and for the processes.

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