Quality assurance in building construction, based on engineering geodesy processes

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Key words: Engineering survey, building construction, quality assurance, quality model,

Monte Carlo simulation

SUMMARY

This article will first introduce the reference project "climbing formwork" and the formal model of the construction processes, on which the further research activities are based on. In addition the interface between construction processes and engineering geodesy processes is modeled in detail. A special focus is drawn on the integration of engineering geodesy processes.

In the following section a quality assurance concept based on a quality model, which consists of characteristics and parameters is presented. On the base of product and process orientated parameters, firstly a complete description of the geometric quality is possible. Then quality evaluation and quality assurance measures are presented.

In the last section numerical Monte Carlo simulations are shown which demonstrate the impact of several input parameters of geodetic processes on the output parameters, that are required within the construction process.

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1. CONSTRUCTION PROCESSES

1.1 Theoretical reference project: climbing formwork

Today construction of high-rise buildings is a highly optimized process involving many different disciplines and participants. However, the perception of quality within these different disciplines is still very different. E. g. matching the required constant tolerances of elevator shafts is a challenging task during the concrete works. To meet these challenges an interaction between construction and geodesy is required.

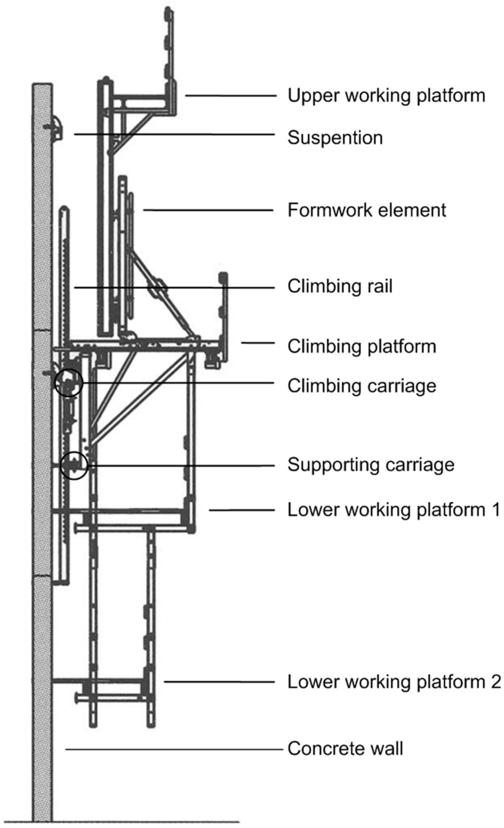

Figure 1: Climbing formwork

In the scientific study described herein a method of quality assurance in construction based on engineering geodesy was developed. The method was theoretically applied to construction of a core of a typical high-rise building. For the concrete works the representative technique of climbing formwork was selected. Figure 1 shows details of a climbing formwork.

Climbing formwork systems are used when horizontal supporting building elements, like slabs or beams, are not available. This situation occurs for example in cores of high-rise buildings, stairwells, bridge pylons, cooling towers, dams etc. Climbing and sliding formwork systems has proven to be efficient in such cases. These systems are designed to be supported only by means of the elements they produce.

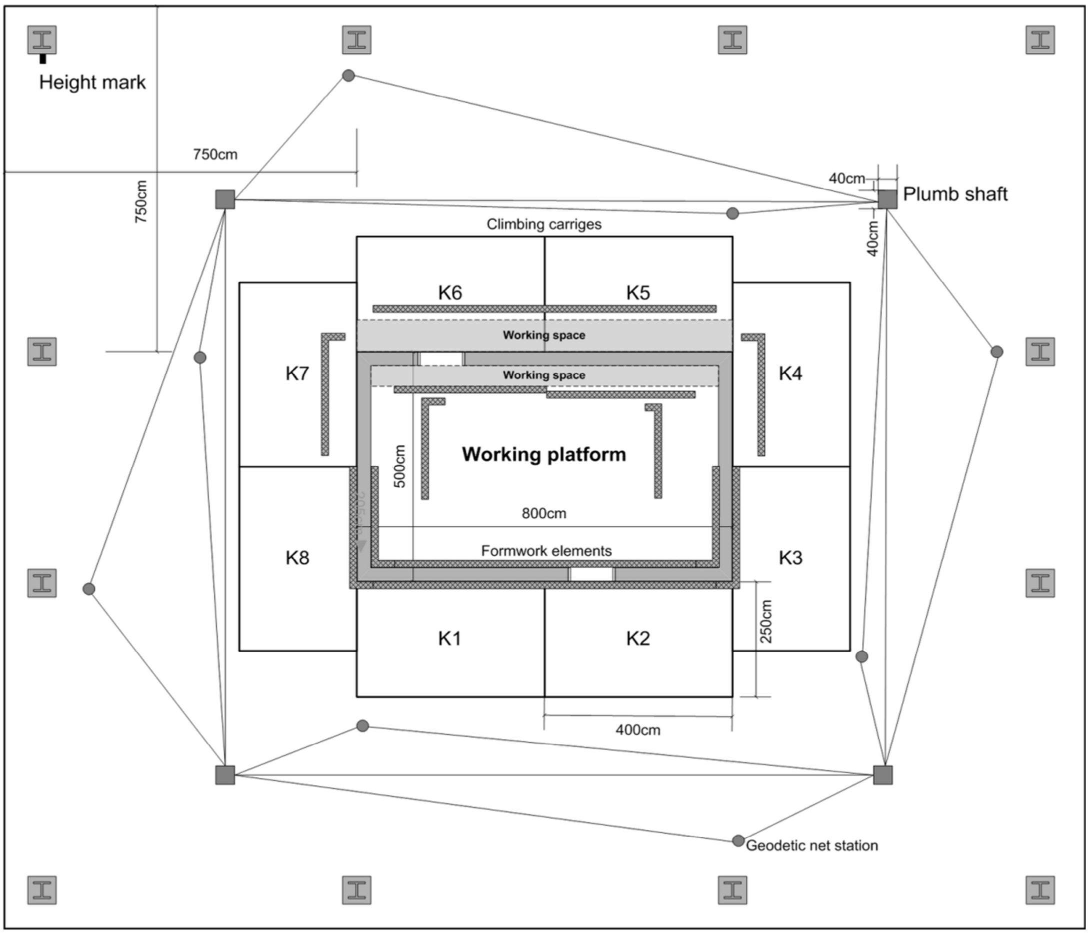

Figure 2: Layout of the typical floor

Climbing formworks can be generally divided into self-climbing and crane-depending (Schmitt, 2001). However, in the presented scientific study the crane-depending climbing formwork was omitted. Only the working platform inside of the building's core (Figure 2) was considered to be displaced by a crane. The formwork itself is supposed to be moved hydraulically. In this manner, the crane capacity relief can be achieved and a nearly wind-independent construction process is possible.

The production process is based on repeating procedures and is set up as a working cycle almost regardless of the height in which works are carried out.
The climbing formwork consists mainly of a large-scaled standard wall formwork, mounted on a climbing carriage and suspended in the hardened concrete of the section made previously (compare Figure 1).

To raise the formwork for the production of the current wall section special platforms based on rail-suspended carriages are used. These platforms also act as working platforms and protective scaffolding. After pouring concrete of the section, the formwork remains in place until hardened of concrete is completed. Then the hydraulic climbing can proceed to the next section. Operating this way the climbing formwork has an advance of one or two stories comparing to the next slab, which incorporates certain challenges to the geodetic surveying.

Additionally to the climbing carriages around the buildings core (Figure 2) on each floor a net of 3-dimensional geodetic points have to be created. It is important for the surveying procedure regarding the climbing formwork.

1.2 Formal model of the build process with process hierarchy

Processes that enable the direct implementation of major tasks (e.g. product manufacturing) are referred to in theory as main processes. They are complemented by ancillary and supported by auxiliary processes. The relationship between those processes is shown in Figure 3.

Unlike the main processes, ancillary and auxiliary processes do not lead directly to the production progress, but would rather aim at the indirect implementation of the sub-tasks. The ancillary processes differ from the main processes only in their purpose. They do not include the production of the original product, but the production of necessary supporting products such as packaging in case of consumer goods. Considering construction site, transport of a formwork from the storage yard to the site could represent such an ancillary process.

Auxiliary processes, however, could be necessary to perform either main or ancillary processes (Figure 3). Even though they do not support for the direct manufacturing progress, they are an indirect requirement for both main and ancillary processes. Examples of auxiliary processes are maintenance, disposal, environmental protection such as air, water purification, waste treatment etc.

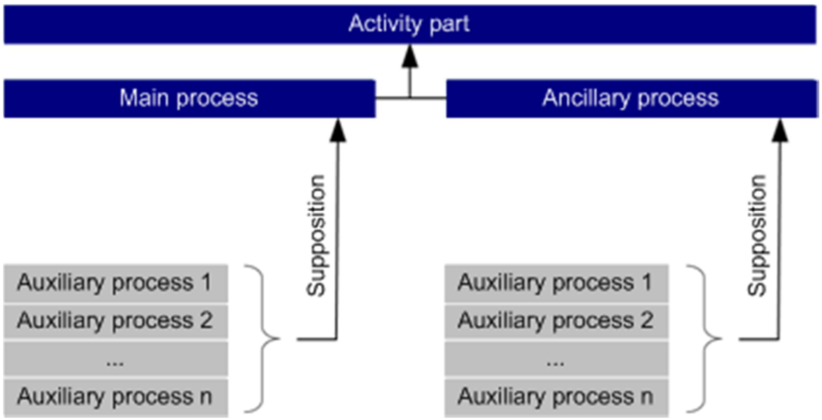

Figure 3: Process classification (Berkhan et al, 2010)

Within construction projects all activities can be considered to consist of macro and micro steps.

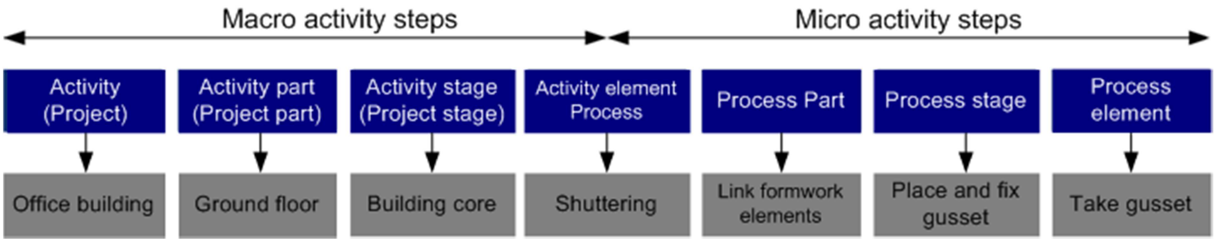

Figure 4: Activity steps shown on formwork (Berner, 1983)

The above mentioned subdivision of activities and processes in parts and elements (Figure 4) was chosen to be the base for the modeling of the construction of the building core. This subdivision was transformed into different hierarchical levels of Petri nets (place transition nets) (Figure 5). A Petri net is a bipartite graph where the nodes are the transitions (rectangles) and the places are the conditions (circle). Simply it can be said, that the transition represent the processes and the places represent a state or a situation. In this contribution the Petri nets are used for representation only. The advantage of Petri nets is the consideration of time. Therefore the optimization of processes with respect to time is an important application (Rehr, 2010). Further information about Petri nets regarding construction process simulation can be found in Berkhan et al (2010).

From the project description, the modeling procedure is focused on the project stage “the creation of the shell construction”. Therefore the modeling process includes three activity steps (see Figure 4), the “Activity element Process”, the “Process part” and the “Process stage”. The last activity step “Process element” is too detailed for modeling regarding the time period of the project. So the process model (see Figure 5) covers 3 hierarchy levels. The first hierarchical level includes the creation of the building core and the corresponding slab, which is complete visualized in Figure 5. From the second and the third hierarchy level only a part can be visualized because the total number of processes, which are modeled within this project, is about 260 for each storey.

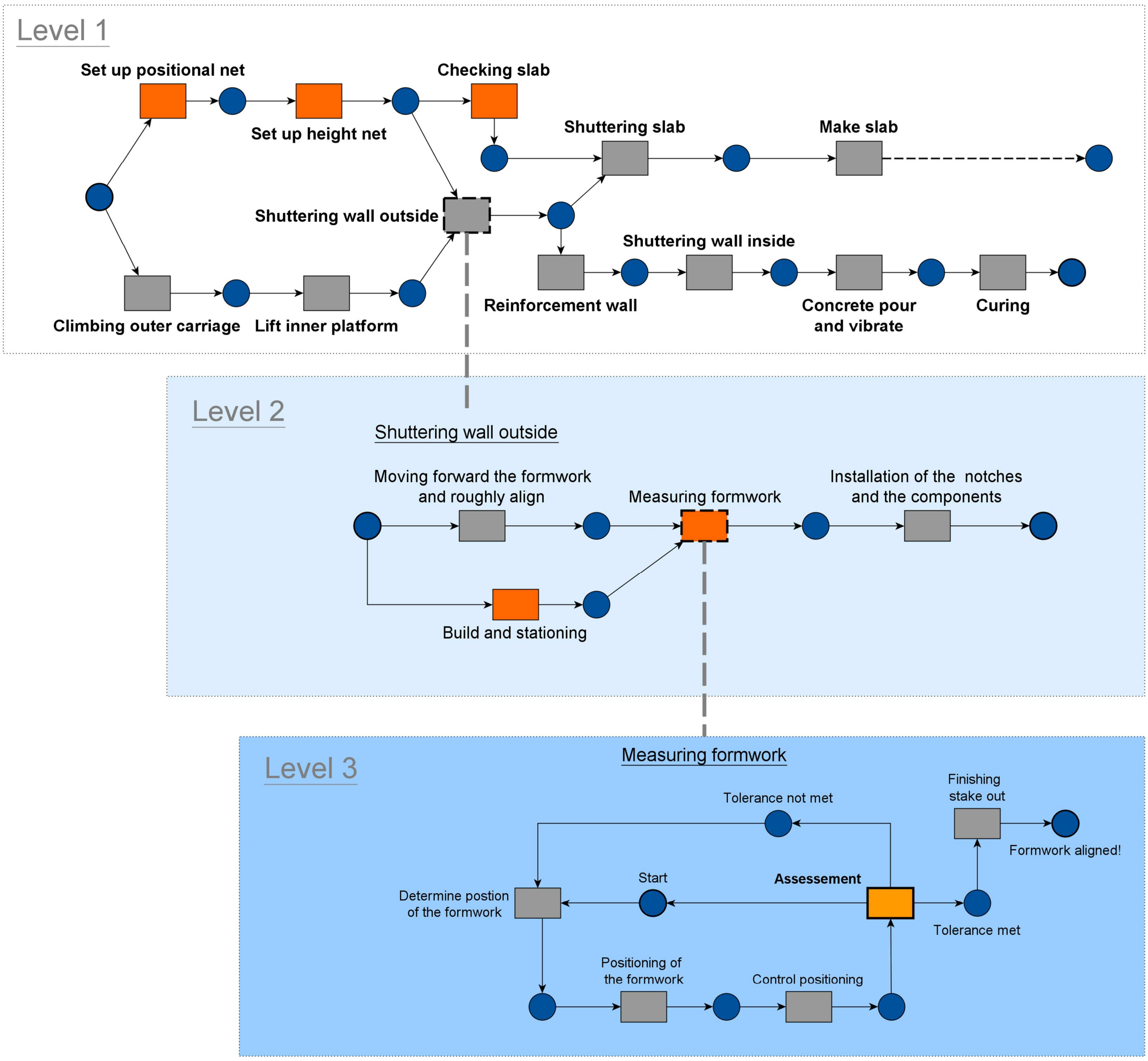

Figure 5: Different levels of hierarchy in the process model (construction and engineering geodesy processes)

The hierarchization is visualized by the dashed transitions shown in Figure 5, which are substantiated by sub Petri nets, which represent the next hierarchy level. The period of time used for one storey-cycle in the model used in the project is one week Monday to Friday. E. g. the process (activity element) “Shuttering” shown in Level 1 in Figure 5 consists of 8 process parts and of 50 process stages. Shuttering takes approximately 400 minutes per storey.

1.3 Integration of engineering geodesy processes into construction processes

In buildings erection a potential increase in quality of construction can be achieved through an optimized interface and better integration of the engineering geodesy processes. Particularly different tolerance specifications and accuracy requirements within the interdisciplinary interface between mechanical engineering and construction can lead to considerable time and cost problems. E.g. this could be the case, if the elevator shaft machinery has to be changed and adopted to match the shaft geometry resulting from concrete works.

To prevent such inadequacy engineering geodesy is normally involved in the whole process of building construction. The interaction between geodetic and construction processes takes place at different stages of construction works in recurring manner. Therefore the precise coordination of this interface is crucial especially regarding well coordinated and repetitious process like use of climbing formwork.

The orange transitions in Figure 5 (e.g. “Set up positional net”, “Set up height net” or “Measuring formwork”) picture the engineering geodesy processes, which are integrated into the construction process. For example in the second hierarchy level, the processes “Build and stationing” is running parallel to construction process “Moving forward…”. Only when both the processes are finished successfully the next engineering geodesy process “Measuring formwork” can start. If the process “Measuring formwork” is successfully finished (tolerance is met) a feedback to construction process is done and the following process “Installation of the notches and the components” is executed. In Figure 6 the process measuring formwork is visualized by a 3D model. Here a total station which is stationed on the last concreted floor is performing the alignment of the formwork.

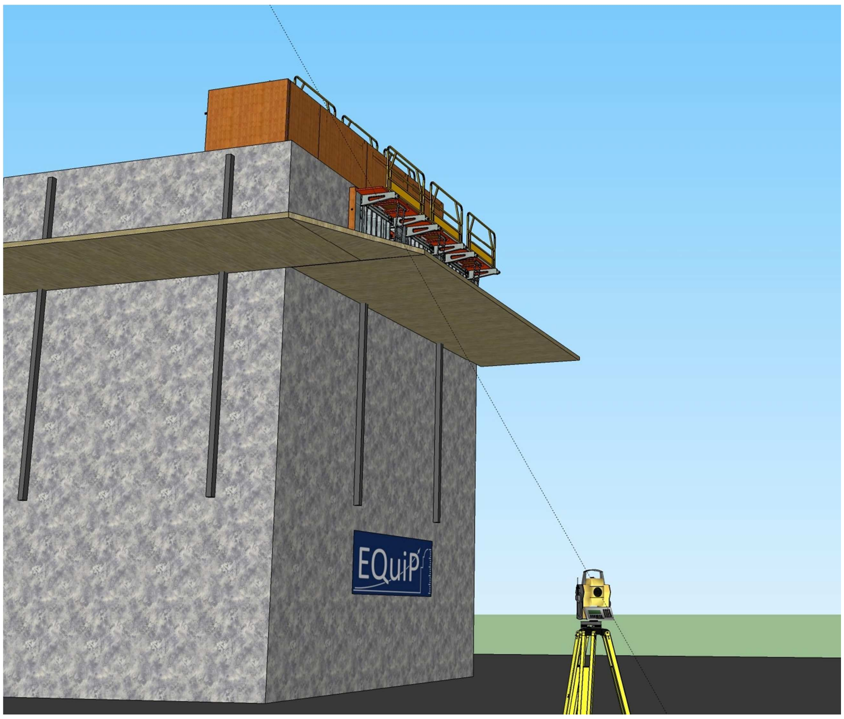

Figure 6: Alignment of formwork by total station

2. GEOMETRIC QUALITY ASSURANCE OF ENGINEERING GEODESY PROCESSES

2.1 Quality assurance concept

In general terms quality assurance includes measures to meet the required quality. It is necessary to prevent errors (not finding the mistakes) (Sehlz, 2010). In our case it is based on a quality model which is a conceptual framework in which the abstract term of quality is gradually resolved into individual aspects. It typically consists of characteristics and parameters. A quality characteristic is an inherent feature of a product or process, related to a requirement (see Figure 7). Each characteristic may be described by a number of parameters. The parameters substantiate the characteristics. Each parameter may be quantified with a specific (measurable) value.

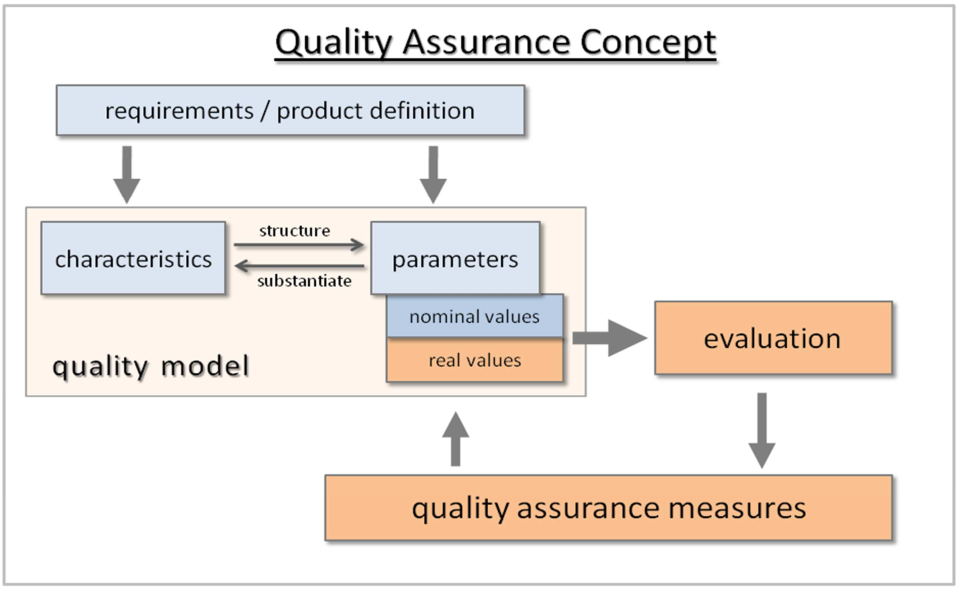

Figure 7: Quality assurance concept

On the base of the quality model which can be derived from the requirements or the product definitions and the real parameter values derived from the measurements, an evaluation can be proceed. The parameter values are evaluated and appropriate quality assurance measures are taken to adjust the quality.

2.1.1 Quality model for engineering geodesy processes

On the base of a requirement analysis, a quality model for engineering geodesy processes in civil engineering is developed (see Table 1). It is consisting of classical geodetic accuracy and reliability parameters but also others like correctness and completeness parameters. The aim is to have a complete description of the quality related to the building geometry. Additionally besides product orientated parameters also process oriented parameters like “Adherence to the plan” and “Time delay” are available.

Table 1: Characteristics and parameters of the quality model

Parameters	Characteristics
Standard deviation	Accuracy
Tolerance correctness Topological correctness	Correctness
Number of missing/ odd elements Adherence to the plan	Completeness
Condition density Minimal detectable error (mde) Impact of mde on parameters Vulnerability to failures	Reliability
Time delay	Timeliness

Details about the derivation and the development of this specific quality model can be found in Schweitzer and Schwieger (2011).

2.1.2 Exemplary parameters

Exemplary, two parameters of the quality model from Table 1 are chosen and explained in detail:
The **standard deviation** σ is a parameter for the characteristic accuracy. It is derived from the random scatter of the measurements x_i of a random variable X around the expected value $E(X)=\mu$. The standard deviation can be calculated from repetitions (see equation 1) or derived from accuracy information of e.g. the measurement device manufactures. To ensure accuracy of two or three dimensional variables, such as points, a covariance matrix has to be used (for detailed information see Teunissen (2003)).

$$\sigma = \sqrt{\frac{(x_i-\mu)^2}{n}} \tag{1}$$

The **tolerance correctness** *tc* is a parameter substantiating the characteristic correctness. It is an aggregated value that delivers a statement of compliance with the required tolerance. It always relies on the measured length of a building component. If *tc* is greater or equal than zero, the tolerance is met. If *tc* is negative, the tolerance is not met (see equation 2).

$$tc = \frac{1}{2}\sqrt{T^2 - T_M^2} - |l_{meas} - l_{nom}| \tag{2}$$

The tolerance T is a specified value, which can be taken for example from standards like DIN 18202. l_{meas} is the measured size and l_{nom} is the nominal size of a building component (compare Figure 8). The surveying tolerance T_M is a tolerance value, which is derived from the uncertainty of the measuring device. The uncertainty is usually expressed by the standard deviation (see equation 3).

$$T_M = 2k_{1-\alpha/2}\sigma \tag{3}$$

The factor $k_{1-\alpha/2}$ is regarded as a quantile of the corresponding distribution function with the given error probability α. Normally the normal distribution is assumed leading to a factor of

$k=2$ for an α of 5%. The surveying tolerance is equal to the length of the confidence interval. Further information on this topic can be found in Schweitzer and Schwieger (2011).

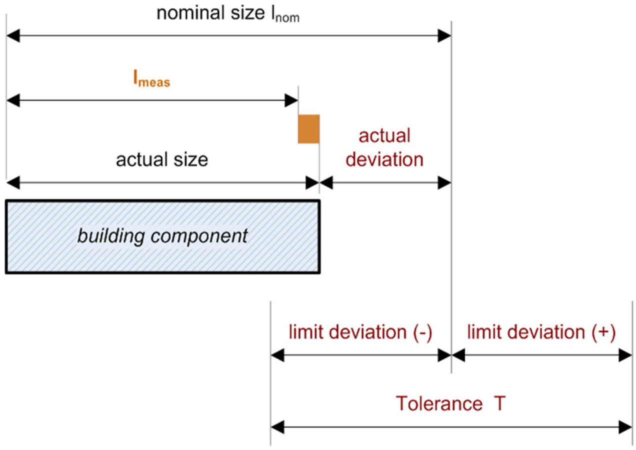

Figure 8: Use of terms in the field of building tolerances (translated and modified from DIN 18202)

2.2 Closed loop system for construction control

For the reference project “climbing formwork” the quality assurance process can be seen in the first hierarchy level (“Set up positional/height net” and “Checking slab”) and in the second hierarchy level (“measuring formwork”) (see Figure 5). The measurements are performed among others with a total station and are the basis for quality description using well-chosen quality parameters which are derived from the quality model (see Table 1). The sequence ”real parameter values”, ”evaluate” and ”quality assurance measures” (from Figure 7) can be seen as a closed loop system which is known from the control theory (see Figure 9). Basics about control theory can be found in Levine (1996) or Lunze (2010).

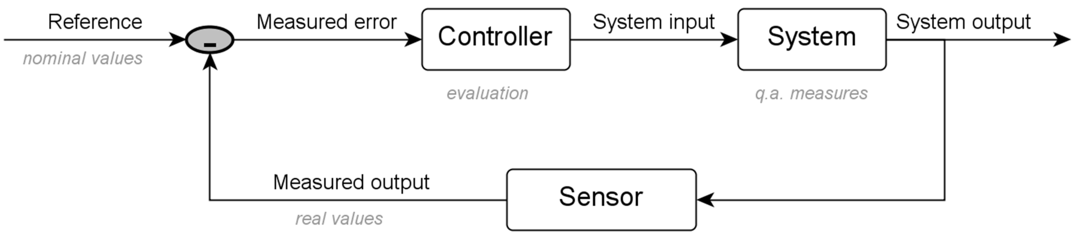

Figure 9: Closed loop system

Related to our quality concept, the “Reference” from Figure 9 is the nominal value which is compared with the “Measured output”, the real values. The controller from the control theory corresponds to evaluation process of the quality assurance concept.

In Möhlenbrink and Schwieger (2007) there are two different closed loop systems regarding the construction control. An outer loop, which deals with the construction control and an inner loop which deals with the technical control of special sub processes like manufacturing machines. Applied to our exemplary process models (Figure 5), the outer control loop containing the construction of the building core and the corresponding floor and the inner loop contains the alignment of the climbing formwork ("Measuring formwork").

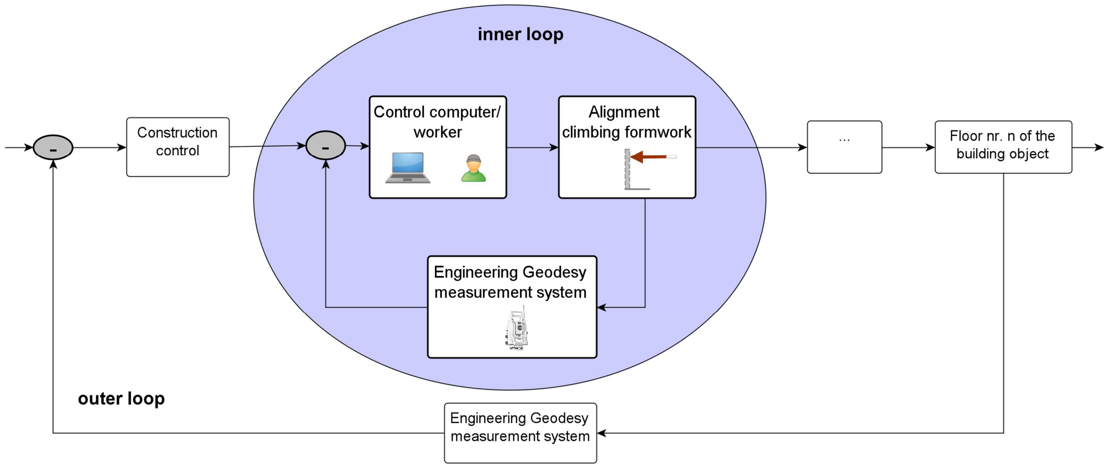

Figure 10: Inner and outer closed loop system for climbing formwork (modified from Möhlenbrink and Schwieger (2007))

The inner loop has to act in real time (within few seconds until minutes). Here the parameter "Tolerance correctness" is evaluated ("Tolerance met") and a correctness information (yes/no) is given back to the construction process. The outer loop cannot be act in real time. The measured error can only be used as knowledge for the further processes or additional, unplanned measures to correct the abuses at the building object. Here additional quality parameters like "Adherence to the plan", "Number of missing elements", etc. can be returned to the construction process.
This closed loop system can be seen as basis for the development of automatic measurement systems in civil engineering. An example in the area of machine guidance is presented in Beetz and Schwieger (2010).

3. SIMULATION STUDIES

3.1 Planning Phase

The simulation studies are focused on the inner control loop only. They can be used to show the impact of different input quantities and measurement configurations on the results.
The exemplary parameters from section 2.1 are taken to explain the propagation procedure. For the parameter standard deviation the Monte Carlo Method is used. For the parameter tolerance correctness additional the quadratic tolerance propagation law is used (compare with Schweitzer and Schwieger (2010)).

3.1.1 Monte Carlo Method

The Monte Carlo Method (MCM) is a numerical method to propagate random variables through a process or a system. A large number *m* of scattered observations are generated computer-based in a "virtual experiment", whose impact on the outcome is determined. It also ensures that each scatter of the input variables $X_1, . . . ,X_l$ suffice his statistical probability distribution. With each sample, the functional model $f (X_1... X_l)$ is going through the calculation and thus gives results $y = f (x)$. On the basis of the m results, a statistical analysis is performed. Important statistical parameters like the expected value μ, the standard deviation σ and the confidence interval $[C_l,C_u]$, can be determined empirically. For further information, see Koch (2008) or Binder (1971).

3.1.2 Numerical example

On the base of the dimensions in Figure 2 and the input parameter values from Table 2 a simulation can be done based on the MCM. As input parameter values, the standard deviation for the control points is assumed to an amount of *5 mm*, the standard deviation for the observations (corresponds to the accuracy level of the total station *Leica TS30*) is assumed to an amount of *0.3 mgon* for the angles and *1 mm* for the distance. For the generating of the random samples the information of the probability distribution is necessary. In our case all the parameters are assumed as normal distributed. The number of random samples for each input variable was set to *10 000*. The stake out objects is a line consisting of two corner points at an upper and lower corner of a formwork element (e.g. K5 from Figure 2).

Table 2: Processes with input and output information

Process	Input / output variables	Input parameter values
Build and Stationing	*Input:* *3 x control points* *9 observations (hz-, v-angle, distance)* *Output:* *1 x* ***station coordinates***	σ_{xyz}=0.005 m $\sigma_{hz,v}$ =0.0003 gon σ_d =0.001 m
Measuring Formwork	*Input:* ***station coordinates*** *observations (hz-, v-angle, distance)* *Output:* *2 x* ***stake out points*** *1 x t**olerance***	$\sigma_{hz,v}$ =0.0003 gon σ_d =0.001 m

The result of the stake out process is a variance covariance matrix of each point and the tolerance correctness *tc* of the line segment (consisting of two points *A* and *B*). For the calculation of *tc* in Table 3 the values l_{meas} and l_{nom} are assumed as equal, because there are no real measurements available for the simulation case. The numeric values for *tc* in Table 3 show the maximum difference between l_{nom} and l_{meas} that would deliver a positive *tc*, if real measurements would be available. A detailed description of the numerical example (including the functional model, the probability density function regarding the output variables and the number of random samples) can be found in Schweitzer and Schwieger (2012).

Table 3: Numerical output

Parameter	Output parameter values
stdv	A: σ_x = 3.2 mm σ_y =3.2 mm σ_z = 3.1 mm B: σ_x = 3.1 mm σ_y =3.2 mm σ_z = 3.1 mm
tc	*tc=14.5mm* (T_M=6.6mm)

3.2 Real time phase

In real time the real parameter values are derived from the measurements. A quality assurance measure is the use of alternative paths. Alternative paths are alternative process chains which can be chosen, if the evaluation of the real parameter values exceed specific predefinde treshholds. This decision has to be made in real time. Therefore it is necessary to define the alternative paths before the execution of construction, in the planning phase. In Figure 11 the process chain of the hierarchy level 2 from Figure 5 is extended by an alternative path.

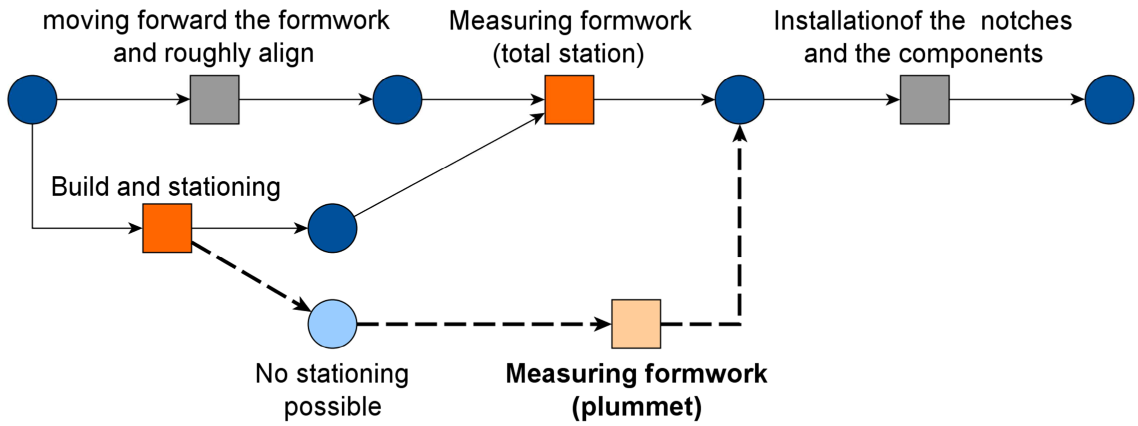

Figure 11: Example of an alternative path

If the process "Build and stationing" cannot be finished properly (e.g. too less control points or the accuracy of the station point is not sufficient), an alternative measuring process (e.g. laser plummet) can be chosen. The original process "Measuring formwork" is not executed. The alternative path can also be simulated by the MCM in the planning phase.

4. SUMMARY

This contribution show research activities related to quality assurance in building construction based on engineering geodesy processes. It is a collaborative work between Civil- and geodetic Engineers, which places special emphasis on the interface between construction and geodetic processes. As a result, the quality assurance concept for building geometry of a high rise building can be emphasized, while a quality model for engineering geodesy processes describes the geometric quality and returns quality information to the construction processes. This can happen in real time and in the planning phase.
Further research activities regarding a stronger integration of the quality parameters in the construction process are planned.

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