Real Time Quality Assurance Indexes for Residential Houses Construction Processes

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Key words: quality model, quality assurance index, real time, construction process

SUMMARY

The EU-project "Development of a Real Time Quality Support System for the Houses Construction Industry" (QuCon) was introduced in Schwieger et al. (2010). Within this project, the Institute of Engineering Geodesy (IIGS) is developing a real time quality assurance system together with further partners from Cyprus. A construction process model and a quality model which considers both process and product quality was developed and defined for residential houses construction processes. In this article an adopted quality model will be introduced which is more application-oriented. Respecting this adopted quality model, a real time quality index can be determined by a scoring system using so-called "checkpoints". The scoring and the weighting of the checkpoints will be discussed. Using the developed construction process model and the scoring system the small and medium enterprises (SMEs) of different countries can monitor the current project states, document the processes and the achieved quality, so that reasonable decisions and corrective can be initiated and the quality can be improved and assured in real time.

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1. INTRODUCTION

In the construction industry everyone is well aware that quality control gets more and more important, because inefficient or lack of quality management or quality assurance leads to needless time and money consumption. There are nowadays numerous researches on the improvement of construction processes, which deals indirectly with the topic "quality". For example, new technologies were integrated into the construction process to monitor the process and enhance the communication among the participants.

Within the EU-project "Development of a Real Time Quality Support System for the Houses Construction Industry"(QuCon), the improvement and the assurance of the quality in construction process is realized by using a quality model. The quality model is part of the quality management concept and improves the quality directly throughout the process. In Schwieger et al. (2010) a quality model was developed and defined for residential house construction which takes both process and product quality into account. Besides, the construction process for residential house construction is modeled by means of flow charts, in which the relationships among processes and task groups were included. Those flow charts help the project manager to coordinate the whole construction process. For more information about the project QuCon, the quality model and the construction process model for residential house construction are referred to Schwieger et al. (2010), Cornet (2010) and QuCon (2010d).

In this article, the quality model is improved to match the requirements of the users at first. The focus is on the algorithms for the determination of a real time quality index and this is realized by a scorings system which is developed with respect to the adopted quality model.

2. QUALITY CONTROL IN CONSTRUCTION

2.1 Existing Quality Control Systems in Construction Process

According to DIN EN ISO 9000, quality is defined as "degree to which a set of inherent characteristics fulfils requirements". Concretely, the quality in the construction industry is the fulfillment of requirements of construction product and process. Many projects are doing research on the modeling and monitoring of the process. For instance, in the project "BauKom" (BauKom 2010), the description of the processes is done by means of workflow, which shows dependencies among the processes and task groups and serves as a model. In this way, the coordination among the related participants can be improved. In Kim et al. (2008) and Leung et al. (2008), it was introduced that new technologies are integrated into the construction process. Such as the PDA, wireless network, web based collaborative platform, information management are exerted in the construction process to collect the data of defects on site and transfer the information to the office in real time. In such a way, the communication in the construction process can be enhanced. They focus usually on the improvement of the communication during the process and the quality is improved indirectly. Within the project "CONQUAS 21" in Singapore (BCA 2005), a construction quality assessment system was developed to assure the quality, but only the product quality will be assessed and a quality model is not applied. Hence, none of the projects in the reference list provides a complete quality model for the construction process.

2.2 Quality Model in Construction

The quality model is part of quality management concept. It consists of the quality characteristics which realize the general quality model for the process and product. Moreover, the quality characteristics should match the user's requirement, which means they are application-oriented. Because of the primarily success of quality models in the manufacturing industry, more and more quality models are defined, developed and utilized in different sciences (Schwieger et al. 2010 and Schweitzer & Schwieger 2010).

The quality model can also be applied to improve and assure the quality in construction processes. Within the project QuCon, a quality model for residential houses construction processes was developed and defined at IIGS in Schwieger et al. (2010). Another quality model within construction process was developed also at the IIGS within the project EQuiP (German: Effizienzoptimierung und Qualitätssicherung ingenieurgeodätischer Prozesse im Bauwesen), which is demanded by the DFG (German Research Foundation). For more information is referred to the Berkhahn et al. (2010) and Equip (2010). In contrast to QuCon, Equip focuses on the engineering geodesy processes in civil engineering and the respective quality modeling on parameter level. The QuCon quality model and scoring system should be utilized throughout the whole construction process and the quality is modeled on characteristics level. An overall quality index needs not to be developed within the Equip. In conclusion, it exists until now no real time scoring system regarding the quality model for the whole construction process.

2.3 Adopted Quality Model in QuCon

The developed quality model in Schwieger et al. (2010) contains both process und product related quality characteristics, which describe the "inherent characteristics" of construction processes. Some of the quality characteristics (resources, synchronization and process-correctness) were eliminated after taking the requirements of the users into consideration, because these characteristics were already considered by checkpoints and construction process model. Hence, the adopted quality model is simple, more practical and application-oriented. Figure 1 is the basic element of the adopted quality model. The availability shall be equivalent to an overall quality characteristic, which takes all other characteristics into account and it is defined differently in Wiltschko & Kaufmann (2005). In this paper the determination of the availability will be discussed. For more details, especially the complete structure of the quality model and the corresponding reasons for these improvements is referred to QuCon (2010a) and Wengert & Schwieger (2010).

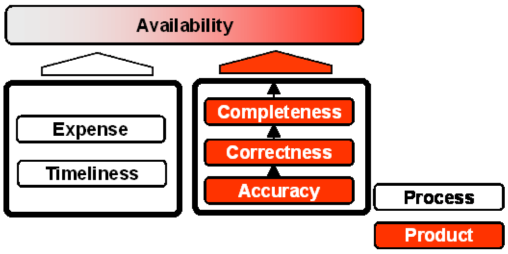

Figure 1: Basic structure of adopted quality model

3. REAL TIME QUALITY ASSURANCE INDEXES

3.1 Basic idea

The so-called "checkpoints" are introduced in Schwieger et al. (2010) as the critical points in the construction processes, which should be checked to avoid damage or financial losses. Because these checkpoints are chronologically integrated in the construction process, they can be used for the calculation of quality indexes in real time. As shown exemplarily in figure 2, the inspector has gone through the checkpoints "site installation" and wants to know the quality index at that point of time.

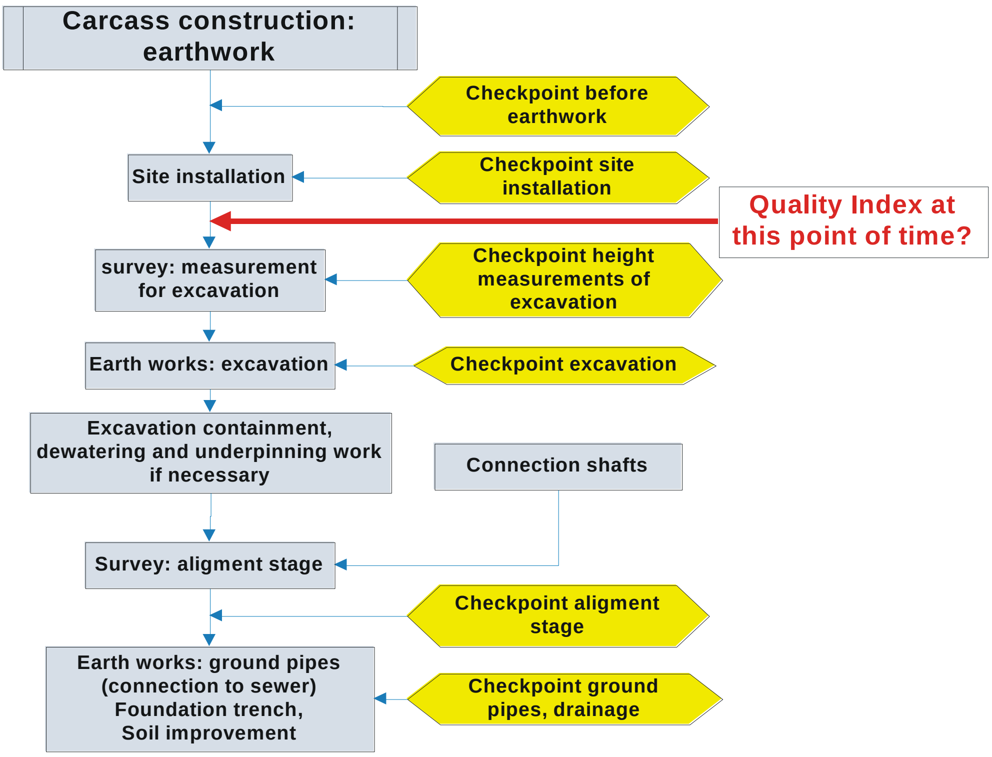

Figure 2: Sub-process with checkpoints

The necessary information for the determination of quality index is the scores and weighting factors of the checkpoints up to this point of time. It is assumed that J checkpoints have been done up to this point of time (checkpoint J),

- Each checkpoint up to checkpoint J has the score S_j,
- Each checkpoint up to checkpoint J has the weighting factor W_j

So the real time quality index up to checkpoint J Q_J can be calculated as:

$$Q_J = \frac{\sum_{j=1}^{j=J} W_j \cdot S_j}{\sum_{j=1}^{j=J} W_j} \tag{1}$$

It means that the real time quality index Q_J is dependent on all the scores and weighting factors up to the checkpoint J. Q_J can be regarded as a weighted mean for the score of checkpoints. In this way, the quality index is independent from the number of checkpoints that have been done (or the stage of the construction process).

The scores and weightings of the checkpoints are inputs for the determination of the real time quality index. In the next sections, the basic elements of the checkpoints will be illustrated and then the determination of the weightings and the scores of checkpoints will be explained.

3.2 Element of the checkpoints

3.2.1 Categories and check items

Usually, a construction process has lots of different task groups such as the structural work, carpenter's work, electrical work, painting work etc, which can be called "categories". In practice, there are quality control lists for different categories. In general, those quality control lists are derived from the literature (Metzger 2010, Meyer 1999), the needs and requirements of the contract, standards, guidelines, general recognized code of practice as well as laws. In Metzger (2010), quality control lists of different categories are given for the residential house construction (see table 1).

1. Quality control list for earthwork
2. Quality control list for structural work
…….
17. Quality control list for floor covering

Table 1: Extract of quality control list in residential house construction (Metzger 2010)

Each category contains so-called "check items", which should be checked by the inspector to ensure the quality. In table 2, some check items of the category "structural work" are presented.

2. Quality control list for structural work

- (2.1) Is the site duly secured?
- (2.2) Is the construction sign (also the one for the authority) installed?
- …….
- (2.63) Are the delivered materials (particularly tiles) compared with the statics (pipe density, compressive resistance)?

Table 2: Extract of quality control list: "structural work" (Metzger 2010)

As shown in table 1 and table 2, the categories and the check items can be numbered. For instance, the category "structural work" has the number 2 and the check items (as presented in table 2) are numbered with the format "X.Y". "X" is the number of category and "Y" is the number of the items. For example, first item in the second category "structural work" has the number 2.1. The numbering of check items is necessary and prepared for the checkpoints (see section 3.3). The applied quality control lists in QuCon are mainly based on the Metzger (2010) and extended by the practitioners. They can be defined by the users individually and updated continuously to match the expectations of users and the market.

3.2.2 Relationship among the categories, check items, checkpoints and processes

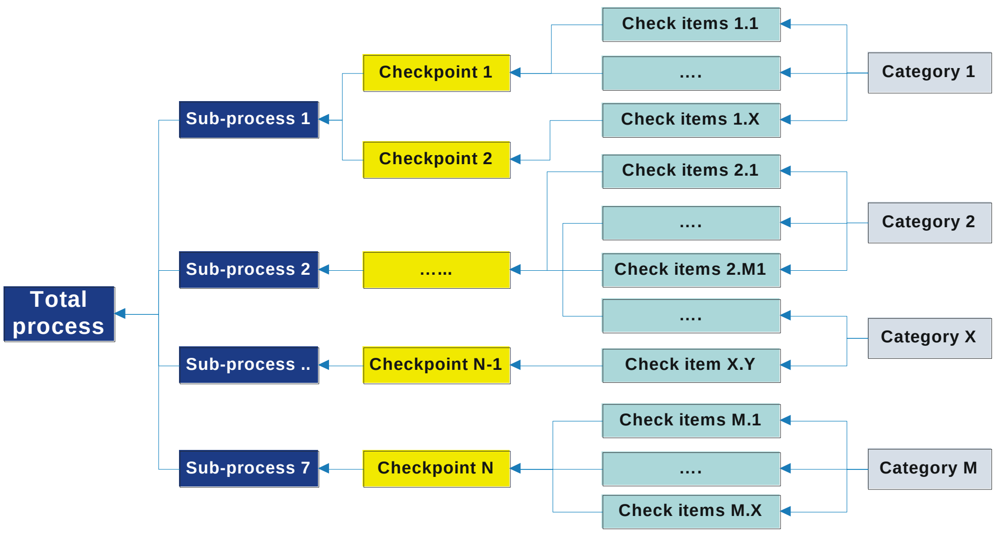

Figure 3: Relationship among the categories, check items, checkpoints and processes

Figure 3 shows the relationship among the checklists, check items and checkpoints as well as the processes. The checkpoints consist of the check items, too. Instead of classification in categories, the check items are chronologically ranged in checkpoints. That means, if the inspection of several check items can be done at the same time, those check items can be then defined as "one checkpoint". Hence, one checkpoint can contain check items that belong to different categories. The checkpoints will be chronologically integrated into the processes. With those the quality can be checked and controlled in real time.

3.3 Determination of Weighting Factor for Checkpoints

3.3.1 Weighting factor for categories

Since the check items are the basic elements of the checkpoints, the weighting factor of the checkpoint can be calculated from its check items. The weightings of check items can be determined from the category, which they belong to.

After the discussion with the SMEs, it comes to a decision that the weighting factors shall base on the construction cost. It means that the more one category costs, the higher it will be weighted. The German team has applied this method for the weighting system. The Cyprus team has defined the weighting factor according to the discussion with the Cyprus SMEs. The following table is the final result of the cost analysis of the German team, which shows the cost percentage for each category on average. (For more information about the cost analysis is referred to the QuCon 2010c, DIN 276-1 2008, DIN 276-4 2009, BKI Baukosten 2010).

Category No.	Category Name	Cost Quotient [%]
1	Earthwork	3.6
2	Structural Work	31.2
	….	…
17	Floor Covering	4.2
Sum		100

Table 3: Extract of cost quotients / weighting factors of categories

3.3.2 Weighting factor for check items

We assume that all the check items in one category have the same weighting; it means they are of the same importance. The weighting factor for the check items can be named as $W_{i,m}$ to be differed from that of categories W_i. So if the category i has the weighting factor W_i and the total number of its check items is M_i, then each check item has the weighting of:

$$W_{i,m} = \frac{W_i}{M_i} \tag{2}$$

So the weighting factor of one check item depends on the category it belongs to. However, we know that some of the critical activities should be fulfilled, for example the basement wall should be water proofing, the entrance door should be there etc. Those “kill process” or “kill activities” should be more important than the other activities, so that they should theoretically have higher weighting. After discussion with the SMEs and the other partners, it was decided to realize the importance of the kill process by an “alarm function” in the software, which helps the user to solve this problem, since a higher weighting would not reflect the importance enough.

3.3.3 Weighting factor for checkpoints

The weighting factor of one checkpoint is calculated from its check items. As the check items may belong to different categories, it is assumed that:

- the checkpoint j has N_i^j check items from the category i,
- the check items in category i have the weighting factor $W_{i,m}$,

then the checkpoint j has the weighting factor W_j:

$$W_j = \sum_{i=1}^{i=numer\_of\_categories} N_i^j \cdot W_{i,m} = \sum_{i=1}^{i=numer\_of\_categories} N_i^j \cdot \frac{W_i}{M_i} \quad (3)$$

For example: the checkpoint j has

- 5 check items from category 1, the category 1 has the weighting factor 10% and contains 10 check items, and
- 3 check items from category 2, the category 2 has the weighting factor 5% and contains 20 check items,

then the weightings of the checkpoint j can be calculated as $W_j = 5 \cdot \frac{10\%}{10} + 3 \cdot \frac{5\%}{20} = 5.75\%$.

3.4 Concept of the Scoring System

3.4.1 Scoring of check items

Not only the weighting but also the scoring of checkpoints is based on the check items, because the check items are scored directly during the inspection. “The scoring scales are defined from 1 to 5: score 1 represents a fail to pass standard/specification’s threshold; score 2 is the threshold; scores 3 to 4 will have a check-specific range of values and finally score 5 will be the maximum quality score” (QuCon 2010b).

There are different types of check: visual, functional and measurable check. The numerical threshold can be clearly defined for the measurable check according to the standards, as the visual and functional check can only be evaluated as “fail” or “pass”. Hence, for the measurable check the score 1 to 5 is possible and for the visual and functional check items only the score 1 or 5 is possible. In the second case, 1 stands for failure and 5 stands for pass.

3.4.2 Scoring and weighting factor step by step

In the next sections, the algorithms for the scoring of checkpoints will be explained step by step. Before the details are presented, an overview of this scoring system is shown in figure 4. First of all, the check items of each checkpoint will be classified according to their characteristics. According to the product related characteristics, all the check items will be separated in 3 families: check items for the completeness, for correctness and for accuracy. The characteristic accuracy is only suitable for the geodetic measurement. The check items can be scored according to the method, which has been described in the section 3.4.1 (step 1).

On one hand the score of the product related characteristics can be determined on the basis of the check items' score; on the other hand the score of the process related characteristics expense and timeliness (compare figure 1) can be calculated from the planned and actual expense as well as the time consumption. Since the algorithms for the scoring of the product and process related quality characteristics are different, they will be explained separately (step2).

For the next step, we can determine not only general scores for product and process related characteristics separately, but also one overall score, which takes both of them into account. This will be the score of one checkpoint (step3).

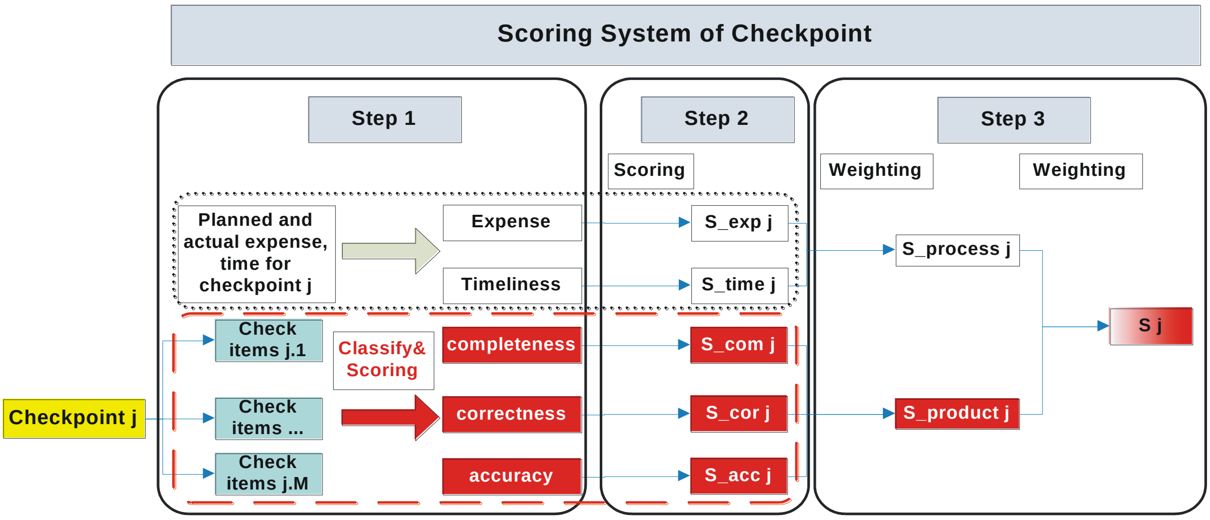

Figure 4: Concept of scoring system for one checkpoint

3.5 Scoring of Quality Characteristics

3.5.1 Scoring of product related quality characteristics

Items & Score	Visual	Functional	Measurable
Completeness	j.1 (1 or 5), …	j.2 (1 or 5), …	j.4 (1 to 5), …
Correctness	j.3 (1 or 5), …	j.7 (1 or 5), ...	j.6 (1 to 5), ...
Accuracy	…	…	j.5 (1 to 5), …

Table 4: Classification of check items

As presented in table 4, the check items of one checkpoint should be at first classified into completeness, correctness and accuracy. Secondly, those check items should be classified into visual check, measurable check and functional check in order to fix the score scale. It is assumed that:

- $S_{n,j}^{com}$, $S_{n,j}^{cor}$ and $S_{n,j}^{acc}$ are the scores of **check items** (in checkpoint j) for completeness, correctness, accuracy, they are between 1 and 5, they will be input by the inspector during the site inspection
- $W_{n,j}^{com}$, $W_{n,j}^{cor}$ and $W_{n,j}^{acc}$ are the weighting factors of **check items** (in checkpoint j) for completeness, correctness, accuracy, they can be calculated as $W_{i,m}$ according to the equation (2), that means:

$$W_{i,m} = \begin{cases} W_{n,j}^{com} & \text{if the check item measures the completeness} \\ W_{n,j}^{cor} & \text{if the check item measures the correctness} \\ W_{n,j}^{acc} & \text{if the check item measures the accuracy} \end{cases} \quad (4)$$

- N_j^{com} , N_j^{cor} and N_j^{acc} are the total numbers of the check items for completeness, correctness and accuracy in the checkpoint j
- S_j^{com} , S_j^{cor} and S_j^{acc} are the product related quality score of **checkpoint j (**between 1 and 5), they will be determined in the scoring system after the equation (5) to (7):

$$S_j^{com} = \frac{\sum_{n=1}^{n=N_j^{com}} W_{n,j}^{com} \cdot S_{n,j}^{com}}{\sum_{n=1}^{n=N_j^{com}} W_{n,j}^{com}} \quad (5)$$

$$S_j^{cor} = \frac{\sum_{n=1}^{n=N_j^{cor}} W_{n,j}^{cor} \cdot S_{n,j}^{cor}}{\sum_{n=1}^{n=N_j^{cor}} W_{n,j}^{cor}} \quad (6)$$

$$S_j^{acc} = \frac{\sum_{n=1}^{n=N_j^{acc}} W_{n,j}^{acc} \cdot S_{n,j}^{acc}}{\sum_{n=1}^{n=N_j^{acc}} W_{n,j}^{acc}} \quad (7)$$

3.5.2 Determination of score for process related quality characteristics

In the last section, the scores of product related quality characteristics of one checkpoint were determined. As shown in figure 5, the score of product related quality characteristics expense and timeliness can be determined by the comparison of actual and planned expense and time consumption:

$$S_j^{\exp} = \frac{E_j^b}{E_j^a} \tag{8}$$

$$S_j^{time} = \frac{T_j^b}{T_j^a} \tag{9}$$

- E_j^a is the actual expense and E_J^b is the budget between checkpoint j-1 and j
- T_j^a is the actual time consumption and T_J^b is the planned time consumption between checkpoint j-1 and j

As the difference between actual and planned expense and time consumption should not be very large, the $S_j^{\exp}$ and S_j^{time} will be around 1. The bigger they are, the better is the quality. This is the same for the product related characteristics (compare section 3.5.2)

3.5.3 Determination of overall quality index

Weightings of quality characteristics

Instead of scores of quality characteristics, it is practical and important for the user to have an overall quality index as an overview. According to the adopted quality model (see figure 1), the availability can be regarded as an overall quality index, which takes both product and process characteristics into consideration. As shown in figure 4, the weighting and score of each other characteristic are necessary for determination of the availability. Besides, the scores of product characteristics are between 1 and 5, but the scores of the process characteristics are around 1. For this reason, the score of product characteristics should be divided by 5, so that they are also around 1. The generic score availability can be calculated as:

$$S_j^{ava} = \frac{\frac{S_j^{com}}{5} \cdot W_j^{com} + \frac{S_j^{cor}}{5} \cdot W_j^{cor} + \frac{S_j^{acc}}{5} \cdot W_j^{acc} + S_j^{\exp} \cdot W_j^{\exp} + S_j^{time} \cdot W_j^{time}}{W_j^{com} + W_j^{cor} + W_j^{acc} + W_j^{\exp} + W_j^{time}} \tag{10}$$

- S_j^{com} , S_j^{cor} and S_j^{acc} are the scores of product characteristics, they are normalized (divided by 5), $S_j^{\exp}$ S_j^{time} are the scores of process characteristics
- $W_j^{com}, W_j^{cor}, W_j^{acc}, W_j^{\exp}$ and W_j^{time} are the weightings of the quality characteristics, those for the product related quality characteristics are defined as:

$$W_j^{com} = \frac{\sum_{n=1}^{n=N_j^{com}} W_{n,j}^{com}}{\sum_{n=1}^{n=N_j^{com}} W_{n,j}^{com} + \sum_{n=1}^{n=N_j^{cor}} W_{n,j}^{cor} + \sum_{n=1}^{n=N_j^{acc}} W_{n,j}^{acc}} \tag{11}$$

$$W_j^{cor} = \frac{\sum_{n=1}^{n=N_j^{cor}} W_{n,j}^{cor}}{\sum_{n=1}^{n=N_j^{com}} W_{n,j}^{com} + \sum_{n=1}^{n=N_j^{cor}} W_{n,j}^{cor} + \sum_{n=1}^{n=N_j^{acc}} W_{n,j}^{acc}} \tag{12}$$

$$W_j^{acc} = \frac{\sum_{n=1}^{n=N_j^{acc}} W_{n,j}^{acc}}{\sum_{n=1}^{n=N_j^{com}} W_{n,j}^{com} + \sum_{n=1}^{n=N_j^{cor}} W_{n,j}^{cor} + \sum_{n=1}^{n=N_j^{acc}} W_{n,j}^{acc}} \tag{13}$$

The weightings of the product characteristics depend on their percentage of the check items. They are different from checkpoint to checkpoint. But their sum is constant: $W_j^{com} + W_j^{cor} + W_j^{acc} = 1$.

The weightings $W_j^{\exp}$ and W_j^{time} can be defined by the users, because each user has his own opinion of the importance of the expense and timeliness compared to the product characteristics. The score gives the users just an overview of the quality, so it is no problem if the weighting factors are different from user to user or from the company to company. We propose for $W_j^{\exp} = W_j^{time} = 0.5$ (so that $W_j^{\exp} + W_j^{time} = 1$) to make the same weighting for product and process related characteristics.

Determination of separate quality index for product and process

Two separate scores for the process and product related characteristics should be given considering the requirements of the SMEs.

Product related overall score of checkpoint j:

$$S_j^{product} = \frac{\frac{S_j^{com}}{5} \cdot W_j^{com} + \frac{S_j^{cor}}{5} \cdot W_j^{cor} + \frac{S_j^{acc}}{5} \cdot W_j^{acc}}{W_j^{com} + W_j^{cor} + W_j^{acc}} \tag{14}$$

since $W_j^{com} + W_j^{cor} + W_j^{acc} = 1$, it can be implied to:

$$S_j^{product} = \frac{S_j^{com}}{5} \cdot W_j^{com} + \frac{S_j^{cor}}{5} \cdot W_j^{cor} + \frac{S_j^{acc}}{5} \cdot W_j^{acc} \tag{15}$$

Process related overall score of checkpoint j:

$$S_j^{process} = \frac{S_j^{\exp} \cdot W_j^{\exp} + S_j^{time} \cdot W_j^{time}}{W_j^{\exp} + W_j^{time}} \tag{16}$$

In this way, each checkpoint has one general quality score S_j^{ava}, one quality score for the product $S_j^{product}$ and one for the $S_j^{process}$ process. As the score of availability S_j^{ava} is an overall quality index of checkpoint j, it is equivalent to the score of checkpoint j S_j in equation (1). As shown in figure 5 and equation (1), each checkpoint has a score S_j, they should be weighted to determine the real time quality index Q_J. Additionally, if the checkpoint j is the last checkpoint in the whole construction process, then the Q_J is the quality index for total process and final product (the house).

To summarize, as presented in figure 5, by using the checkpoints the construction process will be closely combined with the scoring system. The user/ inspector can score the check items within the checkpoints on site and put the planned and actual expense and time consumption in the system, and then the scoring system can run automatically. After the scoring, the alarm will be shown by the failure of the "kill process" and the most important output is the real time quality index Q_J, and then the project manager can go back to the general score of the checkpoint S_j and to the process and product related scores $S_j^{process}$ and $S_j^{product}$. Using the alarm function and the scoring system, the reasonable and necessary action can be carried out. By this means the quality of the construction can be improved and assured in real time.

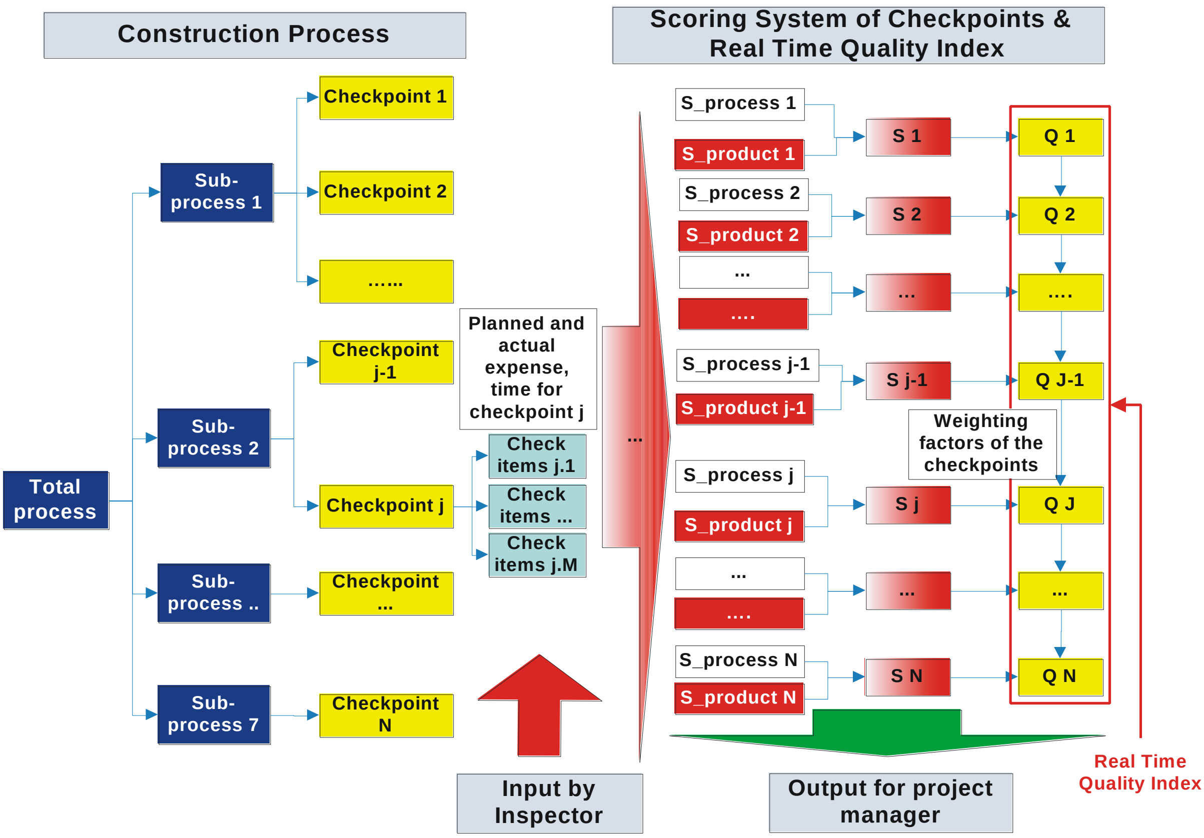

Figure 5: Construction process and scoring system

4. CONCLUSION AND OUTLOOK

Within this paper, an adopted quality model for the residential house is defined and an algorithm for the determination of the real time quality index is described with respect to this adopted quality model. The construction process model serves an overview for the project manager in the software, which will be developed. The checkpoints that contain concrete check items enable the users to document the current project state on site. With this input, the scoring system will run automatically. The results are the real time quality indexes, which will be reported and visualized for the users. The reasonable decision and remediation can be carried out, because the quality of the construction can be documented, checked and accessed in a simple and fast manner, so that it can be improved and assured in real time.

The integration of construction process model into the software was realized by the project partner Synectics. They are proceeding with the implementation of quality scoring system at the moment. The system is web based and the German and Cyprus team as well as the SMEs are going to test the prototype of this system on the web server.

Within the project "CONQUAS 21", different weighting factors are defined for different building types. Similarly, the developed QuCon scoring system is not restricted on the residential house. It can be also applied on the other construction processes, such as high-building, road construction etc. But some adaptations, such as the construction process model, the checkpoints as well as the check items should be correspondingly matched. The quality characteristics can also be fitted to the new construction process, if necessary.

In the future, the checkpoints and check items as well as their weighting factors should be continuously upgraded by the feedback from the end users. Furthermore, many quality checks are based on the contract, generally recognized codes of practice, laws and specially the generally accepted standards, such as ISO, EN and DIN standards. For example in "CONQUAS 21", the minimum standards for each construction component are given. GAEB (2010) gives also lists of the standards (most of them are DIN standards), which are classified according to the categories. Many relevant standards in the housing construction can be found in the project deliverable (QuCon 2009a, 2009b, 2010c). But the collection of all standards is not accomplished in QuCon, because it exceeds already the scope of this project. However, it will be helpful for the users, if the "minimum" standards can be derived from the discussion with the end users, the developers, consultants as well as contractors etc. It may be a massive, challenging but meaningful work for the future. In one word, the system needs strong and continuous feedback, experience, suggestions from exporters and the users in order to match their expectations and have better performance.

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