Considering Quality Aspects for Construction Scheduling using Constraint-Based Simulation

U. Beißert
Chair of Construction Engineering and Management, Bauhaus-University Weimar, Germany

M. König
Chair of Theoretical Methods for Project Management, Bauhaus-University Weimar, Germany

H.-J. Bargstädt
Chair of Construction Engineering and Management, Bauhaus-University Weimar, Germany

ABSTRACT: The specification of effective and robust construction schedules is a challenging task. In construction practice more and more claims are based on quality defects. Therefore, it is necessary to consider quality influences already during construction scheduling. Within this paper the formalization of certain quality aspects and the integration into the constraint-based simulation approach is presented. Experience of workers, qualitative relationship between tasks and available execution time are modeled as the so-called *Quality Control* strategy and represented by using fuzzy soft constraints. If a *Quality Control* soft constraint of a construction task is violated, the requested quality cannot be guaranteed. Thus, using constraint-based simulation valid schedules can be generated considering certain quality demands. Finally, a lab-tested case study of a simplified building storey with certain finishing trades is presented.

1 MOTIVATION

The specification of effective and robust construction schedules is a very complex and challenging task. A multitude of different requirements such as technological dependencies, safety aspects and material availability has to be considered to determine efficient schedules regarding the project objectives time and costs. A third scheduling objective is the quality of the product, which is not considered sufficiently, in today's scheduling practice. Currently, quality aspects are only influenced by the selection of material or the determination of certain inspection dates.

In practice, the quality management standards according to EN ISO 9000 et seq. should help to deliver the contractually guaranteed quality. This norm-family *"… assists organizations … to implement and operate effective quality management systems"*. Therefore, eight different principles have been identified that help to lead the organization towards improved performance. However these principles are targeted on the requirements of the organization and requirements for products, only. In construction environment, these suggestions are mostly put into practice by regular quality checks like material investigations and elements' accuracy. The identification of quality lacks results in reworking or exchanging of elements. Since the exchange of installed elements is difficult and in many cases not possible, most of the defect elements have to be reworked, and not all gain the required quality. Thus, the executing contractor has to face quality claims resulting in a reduction of payments.

The aim is now, to consider more influences on the product quality within the planning process. During the execution a multitude of different influences on product quality exists, such as experience of the workers, process sequencing and available execution time. For example, whenever workers are not experienced enough to execute a certain task, it is assumed that workers are overstrained, and in consequence the quality of the production decreases. Another aspect to achieve good quality is to choose a rugged process sequence, where workers do not obstruct each other and their production.

Within the SIMoFIT cooperation (Simulation of Outfitting Processes in Shipbuilding and Building Engineering) a new approach has been developed to generate construction schedules by using constraint-based simulation (Beißert et al. 2007). In this paper the modeling of the scheduling strategy *Quality Control* is presented to allow the consideration of quality aspects within the constraint-based scheduling process. At first different influencing parameters on product quality are introduced and their impact is investigated. To formalize the strategy, so-called fuzzy soft constraints are used. Then, the *Quality Control* strategy is implemented in the constraint-based simulation approach. Thus, by using event discrete simulation models, valid schedules can be generated considering the quality demands. At the end of the paper a lab-tested case study is presented.

2 CONSTRAINT-BASED SIMULATION

2.1 *Constraint Satisfaction*

Construction scheduling problems can be described by *Constraint Satisfaction*, which is a powerful paradigm for modeling complex combinatorial problems (cf. Balzewicz et al. 2007). Classical constraint satisfaction problems are defined by sets of variables, domains, and constraints. The resulting constraint satisfaction problem (CSP) consists in finding a value combination for all variables, where all associated constraints are fulfilled (cf. Rossi et al. 2006, Kumar 1992).

Generally, constraints are classified into hard and soft constraints to model restrictions and requirements more realistically (cf. Sauer 1998, Dubios et al 2003). Hard constraints have to be fulfilled in order to perform a certain work. By contrast, soft constraints can be violated within a specified range (cf. Freuder et al. 1992). The integration of soft constraints allows the consideration of execution preferences such as execution strategies. The solutions of a so-called partial constraint satisfaction problem are valid execution orders of the construction tasks, where all associated hard constraints are fulfilled and the soft constraints are satisfied as far as possible (cf. Freuder et al. 1992).

2.2 *Construction Constraints*

Modeling the construction scheduling problem, all simulation objects such as tasks, resources, material and equipment are represented by variables. Stringent relations between these variables like execution sequences, resource or material requirements are specified by hard constraints. An overview of some construction hard constraints is given in Table 1.

Table 1. Construction hard constraints (cf. König et al. 2007).

Hard Constraints	
Technological dependencies	Constructional and formal aspects
Capacity	Amount and qualification of employees and equipment
Availability	Supply of material linked to the requirement of storage area
Safety Criteria	Employees' and equipments' protection

2.3 *Execution strategies*

Strategies are proven formal aspects for execution progress. Considering strategies within simulation enables the evaluation of established process sequences or principles. Strategies can be modeled by soft constraints. In Table 2 different well-known execution strategies are specified and classified according to different planning aspects (cf. Beißert et al. 2008a).

Table 2. Execution strategies.

Structural aspects	**Spatial aspects**
Avoid soiling	Closeness
Avoid damage	Distance
Avoid interference	Orientation
Productive aspects	**Qualitative aspects**
Production flow principles	Quality Control
Working spaces	

Within the paper the strategy *Quality Control* is highlighted to consider the influence of different parameters on product quality. Observing this strategy during scheduling will help to guarantee the demanded product quality. The strategy *Quality Control* is implemented using so-called fuzzy soft constraints (cf. Ruttkay 1994). Soft constraints specify practicable or advisable restrictions. The violation of soft constraints is represented by a cost factor. Thus, different execution alternatives can be compared regarding their execution time and costs as well as their strategy costs, which represent the expected lack of quality.

2.4 *Simulation Concept*

Normally, the analytical solution of complex constraint satisfaction problems is very time-consuming. Here, simulation can be used to generate a possible solution very quickly. Therefore, the constraint satisfaction approach was integrated into an event discrete simulation application. The simulation concept enables the generation of different events during the discrete simulation by the procedures *Starting Tasks* and *Stopping Tasks*. Figure 1 shows the procedure starting tasks.

If a new event is upcoming, all not yet started tasks are checked on fulfillment of their associated stringent constraints. All fulfilling tasks are listed as executable. Then those listed tasks are controlled for and ordered by their degree of soft constraint fulfillment. The first task in the list is selected to be started. Its assigned objects, like material resources and employees, are locked during its execution and cannot be used by other tasks. The selection of tasks is repeated until no more tasks can be started at the current time point. If the remaining time of a construction task is expired, the *Stopping Tasks* procedure begins. The task is marked as finished and its assigned objects are released and are now available again for other construction tasks.

Consecutively, the starting and stopping routines are performed until all construction tasks are finished. All events, i.e., starting and finishing tasks as well as locking and unlocking of resources, are recorded. Thus, one simulation run calculates one execution schedule with the corresponding material flow as well as the utilization of employees and equipment.

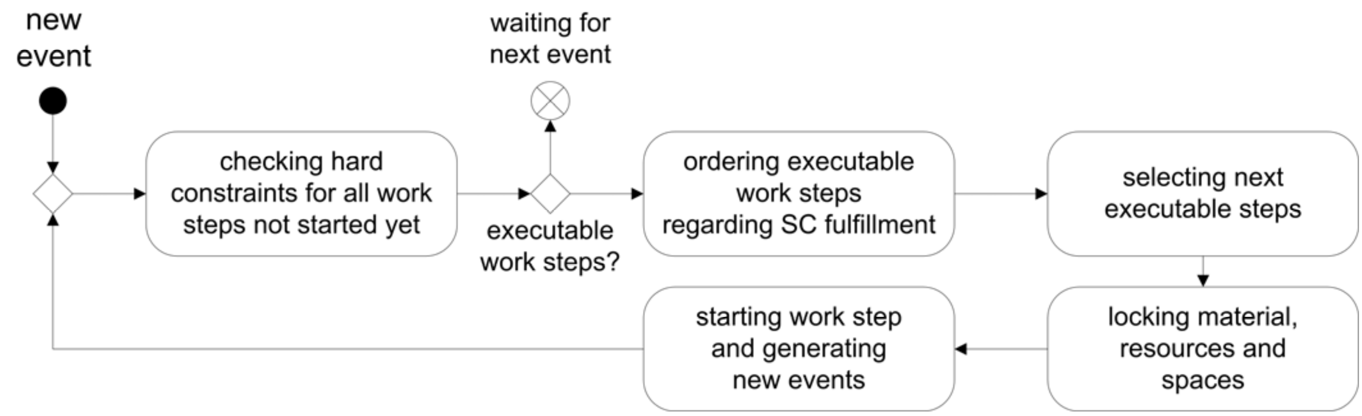

Figure 1. UML diagram *Starting Tasks*.

3 QUALITY ASPECTS

3.1 *Assessment criteria of products quality*

The estimation of quality is very difficult, and the assessment criteria are much diversified. One main aspect is that the desired *building functionality* will be realized. Furthermore, the fulfillment of *dimensional accuracy* and *material characteristics* are strong quality criteria. Newly, quality goes along with the desire for an utmost *flexible building occupancy* and *low life cycle* costs.

3.2 *Execution influences of products quality*

This paper focuses on scheduling of construction tasks. Thus, only quality criteria are investigated, those are influenced by the execution process. A multitude of quality influences are shown in Figure 2 (cf. Koehn et al. 2003). They are ordered by their power of influence on the product quality.

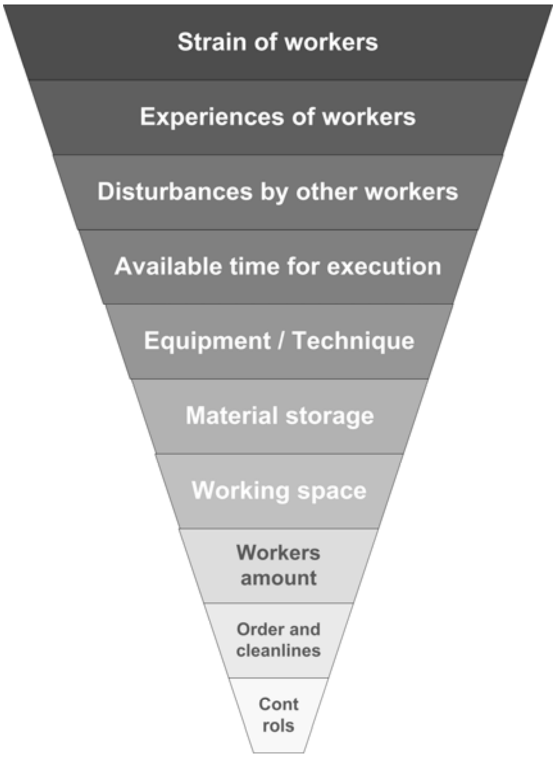

Figure 2. Influences on product quality.

Strain and experience of workers:

Whenever workers are over-strained by physical or mental work, it is assumed that the quality of the resulting product will decline. Under comparable conditions a well experienced worker normally produces better results than an inexperienced one.

Available time for execution:

The estimated execution time for tasks also influences the product quality. If workers execute tasks under time pressure, the accuracy will decline in order to keep the deadline.

Worker Disturbances:

Another aspect to assure good quality is to guarantee sufficient workspace to avoid delaying disturbances and interactions between the workers. Therefore, the workers need a certain workspace to achieve full productivity (cf. Akinci et al. 2002, Mallasi 2004). The influence of the amount of workers goes hand in hand with the previous discussion. Furthermore, an efficient sequence of the processes is necessary to avoid disturbances between work processes. For example, a working area has to be clean enough to execute certain construction tasks and to avoid reworking. Respectively, rough processes should be executed before particular ones and *hidden* processes before *free* ones to avoid damage of already assembled elements.

Material storage and handling

Working equipment and construction techniques, adequate storage conditions and cleanliness of construction sites have great influence on material properties. Improper storage conditions as well as inadequate equipment and execution techniques cause changes of material properties.

3.3 *Scope of the study*

Within this paper, three of the above mentioned influences are considered, formalized and implemented in the strategy *Quality control*. Those are: *experiences of workers*, *disturbances by other work-*

ers and *available execution time*. These parameters seem to be most influencing on the resulting quality.

4 STRATEGY QUALITY CONTROL

4.1 *Experiences of workers*

It is widely known that workers have different degrees of experience. One and the same task executed by a trainee or by a well experienced worker delivers different results. The difference lies in an extension of planned execution time, material excess or even a diminished accuracy of dimensions. The experience of workers is classified as follows:

- Unskilled labor
- Trainee or little experienced worker
- Experienced worker
- High skilled worker

Unskilled labor is not considered, because they are normally not assigned to construction tasks that influence the product quality. Unskilled labor is mostly assigned on extra work like material transport and cleaning jobs. Consequently, the formalization focuses on little-experienced (e-I), experienced (e-II) and high-skilled workers (e-III). Assuming that the execution of each task requires a certain worker experience to provide the best quality, a downward violation of this requirement will cause losses in quality. Contrarily, an upward violation results in under-challenged workers causing a decrease in quality as well. In Table 3 the relationships between required tasks experience and available workers' experience is represented, modeled by normalized resulting quality values q_e.

Table 3. Workers' experience influences on product quality q_e.

Required experience	Workers' experience		
	e-I	e-II	e-III
$R_{e\text{-}I}$	1.00	0.95	0.90
$R_{e\text{-}II}$	0.80	1.00	0.95
$R_{e\text{-}III}$	0.80	0.90	1.00

For example, task A requires for its execution a high-skilled experience worker $R_{e\text{-}III}$ but only experienced workers $R_{e\text{-}II}$ are available. Consequently, the associated quality value is 90%.

4.2 *Work disturbances*

The scheduling of tasks is mostly planned by considering technological dependencies. However, the schedules' compliance with technological dependencies is not sufficient for a good product quality. Different qualitative planning aspects can be considered and specified as additional qualitative dependencies. For example r*ough* activities should be favored before *particulate* activities. Thereby, the damage or soiling of completed construction elements should be avoided, because it causes reworking and therefore unexpected interferences with succeeding processes. Furthermore, *hidden* construction elements should be constructed firstly, to avoid subsequent dismounting for the installation of missing construction elements. For example, if the floor screed works in a room are finished, then the carpet can be passed. However, to guarantee that the carpet is not soiled by other works, at best all floor screed works in this area should be finished before passing the carpet (cf. Figure 3). The violation of these qualitative dependencies results in a reduction of quality by 10%.

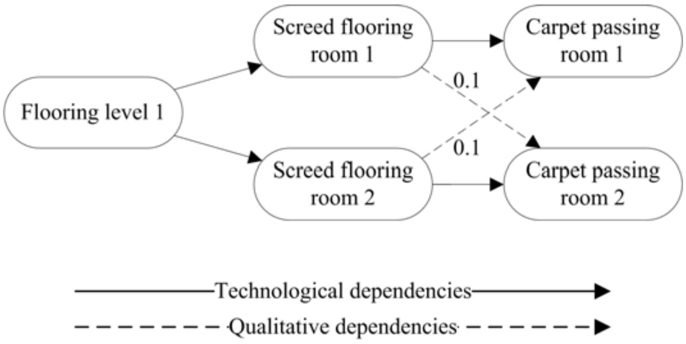

Figure 3. Qualitative dependencies of construction tasks.

Qualitative dependencies can be modeled using additional not stringent relationships between construction tasks. The resulting product quality value of a construction task depends on the amount of fulfilled qualitative dependencies, which are the associated qualitative predecessor tasks. Each qualitative relationship is weighted with a normalized value w_d to guarantee a certain percentage of quality. Attention should be paid, that the aggregation of all predecessor qualitative weights of a certain task is less or equal to 1.0. The quality value q_d for task t can be calculated as follows:

$$q_d := 1 - \sum_{i=1}^{n} w_{d_i} \tag{1}$$

Thereby, n represents the number of qualitative predecessor dependencies of task t.

4.3 *Available execution duration time*

The available duration to execute a task also influences the resulting quality. Time pressure results in diminished execution accuracy and leads consequently to a minor quality. Thereby, critical tasks have more impact on product quality than uncritical tasks. Within this paper critical tasks are for example plastering and painting works, respectively tasks where several successor tasks have to be executed directly upon the finished product of their predecessor. Thus, any lack of accuracy is passed on to the consecutive tasks and cannot be compensated by the successors. Successively, the loss of quality increases during the different phases of production.

In planning practice execution durations are calculated based on well-known standard values for working durations, *ARH* (cf. IZB 2002). However, these values are bound to a multitude of assumptions such as environmental conditions, certain distances to material and equipment storage, etc. Variations of the assumptions result in an extension of needed execution duration. Assuming, that the standard values enable a certain degree of product quality, each time reduction causes a loss of quality, while times' enhancement will deliver an improved quality. According to this assumption, exemplarily, Table 4 shows some critical and uncritical finishing tasks with standard time durations as well as required additional execution time to improve obtainable quality.

Table 4. Time duration and buffers for drywall construction.

Drywall construction	**ARH duration**	**Time buffer**
Calibrating	0.02 h/m	0.002 h/m
Plastering	0.40 h/m²	0.100 h/m²

Currently, this relation is implemented in a simplified way by using a linear function. Whenever a required execution time, using working time standard tables (cf. IZB 2002), is assigned to a task, a certain product quality is accessible represented by a quality factor q_t. Figure 4 depicts the dependency between available execution time and resulting product quality. Within this paper it is assumed, that an available standard execution duration t_{ARH} leads to a quality factor of q_{ARH}. However, depending on the working process not all time extensions result in better quality.

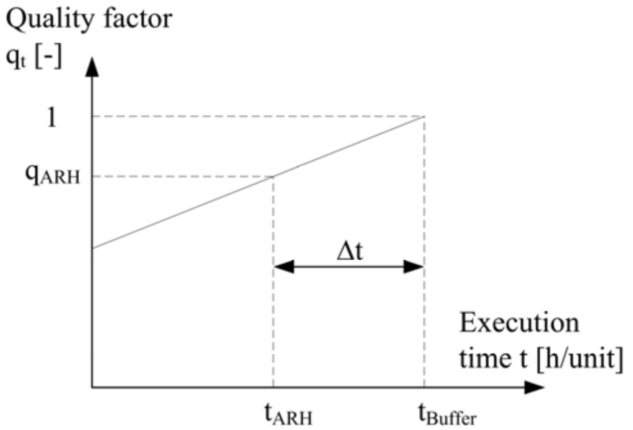

Figure 4. Qualitative execution duration influences q_t.

Consequently, for each task an additional time buffer t_{Buffer} can be specified to consider the influence of available execution time on the resulting quality. The corresponding quality factor q_t. can be calculated by the following linear relation.

$$q_t(t) := 1 - \frac{1-q_{ARH}}{\Delta t}\cdot\left(t_{Buffer}-t\right) \tag{2}$$

4.4 *Fuzzy Soft Constraint Representation*

Execution strategies can be formalized using different soft constraint representations such as weighted, k-weighted or fuzzy constraints (cf. Beißert et al. 2008a, 2008b). In the following fuzzy soft constraints are highlighted to represent the strategy *Quality control*.

A fuzzy constraint describes a fuzzy relation between variables of the constraint satisfaction problem. The fuzzy relation is defined by a membership function $\mu_R := (d_1, \ldots, d_n) \in [0, 1]$, that assigns a level of constraint satisfaction $\mu_R(d_i)$ for each tuple $(d_1, \ldots, d_n)$ (cf. Rossi et al. 2006; Dubois et al. 1995, 2003). Consequently, this assignment leads to different types of constraint fulfillment:

$\mu_R(x) = 1$ totally satisfies
$\mu_R(x) = 0$ totally violates
$\mu_R(x) \in]0, 1[$ partially satisfies

The maximal aggregated fuzzy constraint values represent an optimal solution of a so-called fuzzy constraint satisfaction problem (cf. Rossi et al. 2006).

The implementation's first step is the fuzzyfication of the attribute product quality (cf. Slany 1994). Here the difference is made *low*, *medium* and *high quality*. The fuzzy membership functions are shown in Figure 5. Each degree of quality is clearly specified using a trapezoid fuzzy number. Each trapezoid function is numerically represented by its vertices as follows:

$Q_{low} = [(0, 0); (0, 1); (0.5, 1); (0.75, 0)]$
$Q_{medium} = [(0.5, 0); (0.75, 1); (0.75, 1); (1, 0)]$
$Q_{high} = [(0.75, 0); (1, 1); (1, 1); (1, 0)]$

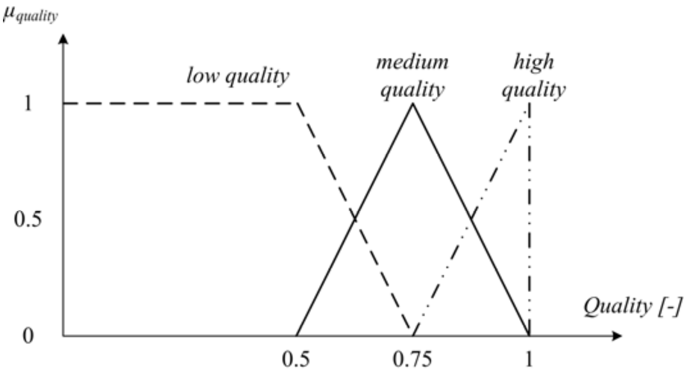

Figure 5. Fuzzy representation of quality.

Using these fuzzy representations of quality the user's demand of product quality can be quantified and therefore considered as soft constraint during planning. Thus, only tasks that fulfill their quality requirements can be executed. The soft constraint fulfillment is checked by using the Height Method to defuzzify the influencing parameters on the product quality (cf. Kahlert 1995, Li et al. 1995).

For example, task *A* fulfills its hard constraints and is listed as next executable task. Next, the soft constraint fulfillment has to be inspected. It is assumed, that the planning engineer has specified to keep a *high product quality*. Table 5 shows the three presented quality factors of the task *A*, which influence the obtainable quality.

Table 5. Quality factors of sample task *A*.

Current parameter task A		**Quality factors**
Experience of worker	q_e	0.8
Qualitative sequence	q_d	0.7
Available execution time	q_t	0.9

The experiences of available workers to execute task *A* result in a diminished quality of 0.8. Furthermore, the suggested qualitative sequence is not completely fulfilled. Thus, the obtainable quality amounts to 0.7. The available execution time does not guarantee a fully qualitative work. The resulting quality will be 0.9. The three parameters have to be defuzzified in order to calculate the total soft constraint fulfillment.

The parameters can be defuzzified using the Height method that results in the representative point (cf. Kahlert 1995). Accordingly, the total quality factor q of a task *A* is calculated by the representative points of the three quality factors q_e, q_d, and q_t and its associated maximum heights h_e, h_d, and h_t (cf. Li et al. 1995).

$$q = \frac{q_e \cdot h_e + q_d \cdot h_d + q_t \cdot h_t}{h_e + h_d + h_t} \tag{3}$$

The different quality factors are considered as singletons (cf. Figure 6).

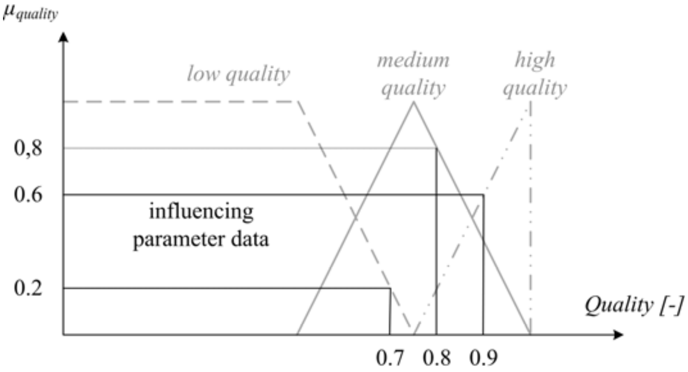

Figure 6. Quality singletons.

Using the singleton of each quality factor the maximum height of each degree of quality is evaluated (Figure 7a). In this example, the application of the Height method for defuzzification leads to the representative total quality factor q = 0.78, which indicates the total influence of the three quality factors.

Thus, the resulting total quality factor q of task *A* is quantified (cf. Figure 7b) and consequently the fulfillment of the soft constraint *high quality* can be determined as: μ_{quality} = (0.0; 0,83; 0.17). Hence, the *Quality Control* soft constraint of task *A* is fulfilled.

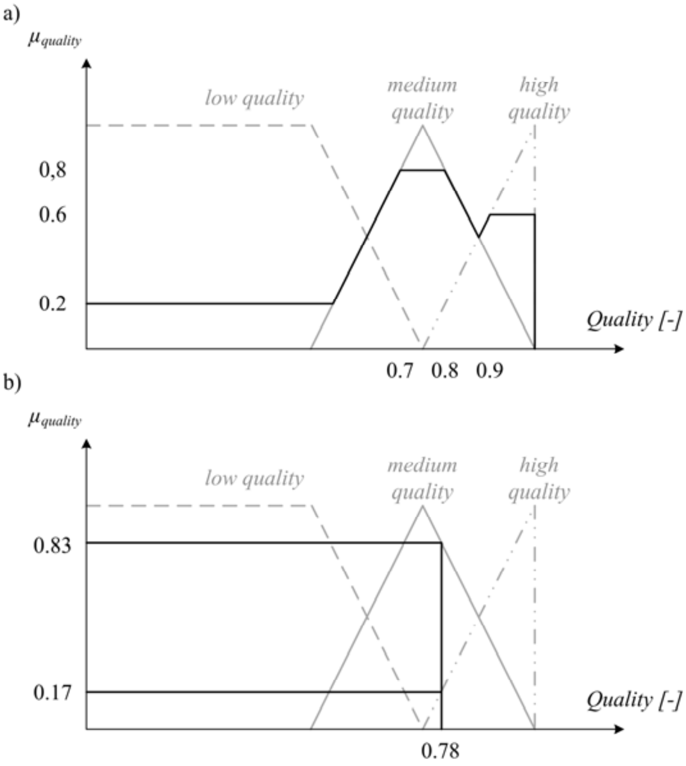

Figure 7. Maximum heights (a) and defuzzified quality (b).

5 IMPLEMENTATION

The fuzzy soft constraint *Quality Control* is integrated into the constraint-based simulation approach. For all construction tasks or a certain group of them a soft constraint *Quality Control* can be specified by selection of one fuzzy value (e.g. *high quality*). To calculate the soft constraint fulfillment of a certain task, the following properties have to be defined manually: required worker experience, qualitative relationships, quality time percentage of standard *ARH* time and time buffer to reach 100% quality in terms of execution durations.

During simulation the procedure *Starting Tasks* (cf. Figure 1) controls all next executable tasks according to their fulfillment. Therefore, at first the influence on product quality caused by the aforementioned parameters has to be determined. The experience quality factor q_e of a task is determined based on certain available workers. The workers, which lead to the highest percentage of quality, are selected and reserved for assignment. The qualitative relationship factor q_d is calculated accordingly to equation (1). The quality factor q_t for available execution time is currently determined by inspecting the following two cases. First, the specified quality factor of standard *ARH* time is used and the associated quality factor q_t is determined. Using the height method the result can be defuzzified. If the resulting quality representative point q (cf. Figure

7b) is located within the requested *Quality Control* fuzzy value, the associated soft constraint is fulfilled. Whenever a fuzzy soft constraint of a task is totally violated, the tasks' quality factor q_t must be improved. Consequently, the execution duration of the regarded task is increased by the specified factor Δt. Following, the total quality and its representative point q is calculated again (cf. Figure 8).

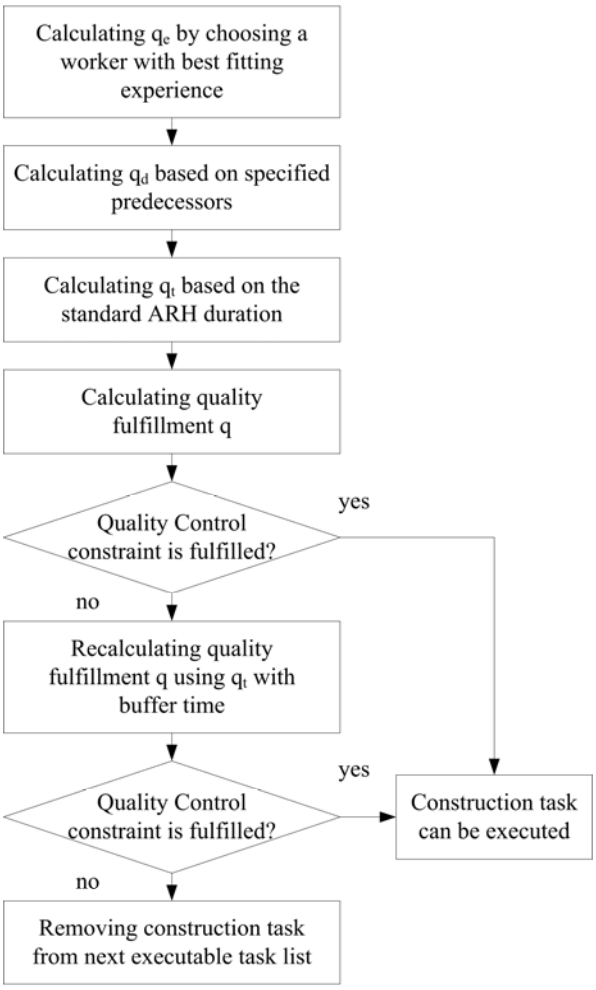

Figure 8. Flow diagram *Quality Control* inspection.

As mentioned before, after calculating quality control satisfaction values for each next executable task, all tasks are ordered by their soft constraint fulfillment. Only tasks can be executed, which at least partially fulfill their *Quality Control* soft constraint (cf. Figure 1). The task, which fulfills the soft constraint at best, is selected to be started. Whenever several executable tasks fulfill their soft constraint at equal measure, one task is selected randomly. The procedure *Starting Tasks* is repeated until no more tasks can be started at the current simulation time point.

6 CASE STUDY

In this section the presented strategy *Quality Control* and its implementation is evaluated by scheduling and analyzing three finishing trades of a building storey with four rooms: drywall construction, floor covering and painting (cf. Figure 9).

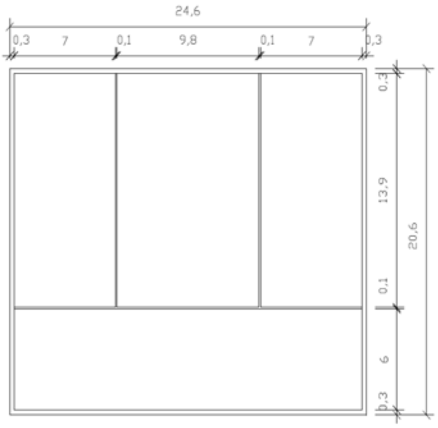

Figure 9. Building storey.

For each trade different construction task types are specified. Construction task types and their required experience q_e are shown in Table 6.

Table 6. Finishing trades and required experience

Drywall construction	q_e
Calibrating	$R_{e\text{-}III}$
Assembling (lower part)	$R_{e\text{-}II}$
Assembling (upper part)	$R_{e\text{-}III}$
Plastering (lower part)	$R_{e\text{-}II}$
Plastering (upper part)	$R_{e\text{-}II}$
Grinding	$R_{e\text{-}II}$
Floor Covering	q_e
Insulating	$R_{e\text{-}II}$
Leveling I	$R_{e\text{-}III}$
Leveling II	$R_{e\text{-}III}$
Laying	$R_{e\text{-}III}$
Painting	q_e
Cleaning	$R_{e\text{-}I}$
Priming	$R_{e\text{-}II}$
Painting 1st	$R_{e\text{-}III}$
Painting 2nd	$R_{e\text{-}III}$

The qualitative relationships and their quality factors q_s are defined as follow (cf. Table 7):

Table 7. Finishing trades and qualitative relationships

Drywall construction	**Successors**	q_d
Calibrating	-	-
Assembling (lower part)	Plastering (lower part)	0.05
Assembling (upper part)	Plastering (upper part)	0.05
Plastering (lower part)	Insulating	0.10
Plastering (upper part)	-	-
Grinding	Cleaning	0.10
Floor Covering	**Successors**	q_d
Insulating	-	-
Leveling I	Assembling (upper part)	0.10
Leveling II	Painting 2nd	0.05
Laying	-	-

Painting	**Successors**	q_d
Cleaning	-	-
Priming	-	-
Painting 1st	Leveling II	0.05
Painting 2nd	Laying	0.10

The duration values of the tasks and their associated quality factors q_b are presented in Table 8.

Table 8. Durations and buffers

Drywall construction	**Duration**	q_{ARH}	**Δt**
Calibrating	0.03	0.75	0.005
Assembling (lower part)	0.54	0.75	0.080
Assembling (upper part)	0.54	0.75	0.080
Plastering (lower part)	0.03	0.80	0.005
Plastering (upper part)	0.03	0.80	0.000
Grinding	0.12	0.75	0.010
Floor Covering	**Duration**	q_{ARH}	**Δt**
Insulating	0.45	0.75	0.040
Leveling I	0.45	0.75	0.090
Leveling II	0.70	0.75	0.140
Laying	0.10	0.90	0.020
Painting	**Duration**	q_{ARH}	**Δt**
Cleaning	0.02	1.00	0.000
Priming	0.06	0.90	0.010
Painting 1st	0.06	0.75	0.015
Painting 2nd	0.06	0.75	0.015

Based on the given number of rooms and drywalls as well as specified finishing trades 742 tasks and 1732 associated hard constraints were generated. For this case study following workers and experiences were specified (cf. Table 9):

Table 9. Workers definition

Worker	**Amount**	**Experience**
Drywallers	3	e-II
Drywaller experts	1	e-III
Drywaller trainees	1	e-I
Floorers	4	e-II
Floorer trainees	2	e-II
Painters	2	e-II
Painters experts	1	e-III
Painter trainees	1	e-I

To analyze the effects of considering *Quality Control* soft constraints within construction scheduling, the variance of the total execution time is investigated. Therefore, 1000 Monte Carlo experiments were simulated and evaluated without consideration of any *Quality Control* constraint (Experiments A). Each Monte Carlo experiment generates one possible schedule based on the constraint-based simulation approach. The next executable tasks are selected randomly during the procedure *Starting Tasks* (cf. Figure 1). An adequate amount of Monte Carlo experiments has to be executed to provide a significant set of solutions. All total execution times, the so-called makespan, are shown in Table 10. The Monte Carlo experiments generate solutions with minimal makespans of 653 hours and an averaged makespan of 695 hours. Subsequently, for the specified product quality values *medium quality* (Experiments B) and *high quality* (Experiments C) also 1000 Monte Carlo simulations were performed. During the procedure *Starting Tasks* (cf. Figure 1) the next executable tasks are ordered considering their accessible quality and the required quality. The tasks that fulfill the soft constraint at best are preferably executed. Each quality is used once as *Quality Control* soft constraint for all construction tasks. The Monte Carlo Simulation results are shown in Table 10.

Table 10. Monte Carlo Simulation results

Monte Carlo Simulation		**Minimal makespan**	**Averaged makespan**
A	Without *Quality Control*	653h	695h
B	*Medium Quality*	654h	695h
C	*High Quality*	660h	700h

The minimal makespan of the Monte Carlo experiments A is marginally better than the minimal makespans of the experiments B and C. Between the minimal makespans of the experiments A and B no significant differences can be seen. In this case study the consideration of the demand for a high quality during scheduling has no major impact on the total execution time. In result, by a systematic and detailed scheduling a short total execution time can be generated that additionally guarantees the demanded product quality.

7 CONCULSION AND OUTLOOK

The scheduling of construction processes in civil engineering is very complex and extensive. A multitude of restrictions and requirements has to be considered as well as principal guidelines must be obeyed, such as time, cost, and quality. Especially, the guarantee of the contracted product quality is a challenging planning task. In this paper a new concept is presented to consider quality aspects for scheduling construction projects as the so-called strategy *Quality Control*. Three different quality aspects are highlighted: experiences of workers, work disturbances and available execution times. The formalization of these aspects leads to three normalized quality factors. To consider a certain quality during scheduling so-called fuzzy soft constraints are used. The requested product quality is represented by a trapezoidal fuzzy number (e.g. *low quality*, *medium quality*, *high quality*). After the aggregation and defuzzification of the quality factors using the well-know Height method the fulfillment of the soft constraint *Quality Control* can be evaluated. Our constraint-based simulation approach is extended to consider the *Quality Control* soft constraint within an event discrete simulation. A case study is presented to evaluate our implemented *Quality Control* concept.

The scientific approach for a valid simulation of construction processes, as presented in this paper, must further on be based on more and sound ergonomic analyses. Up to now, as presented here, the knowledge about the dependencies and interactions from an ergonomics point of view is drawn from substantial practical experience, whereas the analytical achievements concerning qualitative interrelations between performance conditions and quality criteria are still scarce.

Looking again to the technological side of simulation, in future work, the *Quality Control* soft constraint will be extended by other quality aspects (e.g. strain of workers, working space, equipment and execution techniques). Furthermore, multi-objective optimization is projected based on our constraint-based approach to generate efficient construction schedules regarding costs, time, and quality. Therefore, it is assumed to use Meta Heuristics like Simulated Annealing, Swarm Theory or Genetic Algorithms.

8 REFERENCES

Akinci, B.; Fischer, M.; Levitt, R. & Carlson, R. 2002. Formalization and Automation of Time-Space Conflicts Analysis. *Journal of Computing in Civil Engineering* 16(2): 124-134

Beißert, U.; König, M.; Bargstädt, H.-J. 2007. Constraint-Based Simulation of Outfitting Processes in Building Engineering. *24th W78 Conference, Maribor, Slovenia*

Beißert, U.; König, M.; Bargstädt, H.-J. 2008a. Execution strategy investigation using soft constraint-based simulation. *IABSE Conference, Information and Communication Technology (ICT) for Bridges, Buildings and Construction Practice, Helsinki, Finland,* CD-ROM-Publikation

Beißert, U.; König, M.; Bargstädt, H.-J. 2008b. Generation and local improvement of outfitting schedules using constraint-based simulation. *12th ICCCBE Conference, Beijing, China*, CD-ROM-Publication

Balzewicz, J.; Ecker, K.; Pesch, E.; Schmidt, G.; Weglarz, J. 2007. Handbook on scheduling: from theory to applications. *Berlin, Springer*

Dubois, D.; Fargier, H.; Fortemps, P. 2003. Fuzzy scheduling: Modeling flexible constraints vs. coping with incomplete knowledge. *European Journal of Operational Research*, Vol. 147, No. 2, pp. 231-252

Dubois, D.; Fargier, H.; Prade, H. 1995. Fuzzy constraints in job-shop scheduling, *Journal of Intelligent Manufacturing*, Vol. 6, pp. 215-234

EN ISO 9000. 2005. Quality managements systems – Fundamentals and vocabulary. *DIN Deutsches Institut für Normung e.V., Berlin. (Tri-lingual edition English-German-French)*

Freuder, E.C.; Wallace, R. 1992. Partial constraint satisfaction. *Artificial Intelligence*, Vol. 58, pp. 21–70

IZB 2002. Institut für Zeitwirtschaft und Betriebsberatung Bau - ARH Tabellen. *Neu-Isenburg, Zeittechnik-Verlag, Karlsruhe*

Kahlert, J. 1995. Fuzzy Control für Ingenieure. *Vieweg Verlag, Braunschweig/Wiesbaden*

Koehn, E.; Datta, N.K. 2003. Quality, Environmental, and health and Safety Management Systems for Construction Engineering, *Journal of Construction Engineering and Management*, Vol.129, No. 5, pp. 562-569

König, M.; Beißert, U.; Bargstädt, H.-J. 2007. Constraint-based simulation of outfitting processes in ship building and civil engineering. *6th Eurosim Congress in Modelling and Simulation, Ljubljana, Slovenia*

Kumar, V. 1992. Algorithms for Constraint Satisfaction Problems: A Survey. *AI Magazine*, spring 1992, pp. 32-43

Li, H.; Gupta, M. 1995. Fuzzy Logic and Intelligent Systems. *Springer Verlag, Berlin*

Mallasi, Z. 2004. Identification and Visualization of Construction Activities' Workspace Conflicts Utilizing 4D CAD/VR Tools. *1st ASCAAD International Conference e-Design in Architecture, Dhahran, Saudi Arabia*, pp. 235-253

Ruttkay, Z. 1994. Fuzzy constraint satisfaction. *Proceedings of the 3rd IEEE World Congress on Computational Intelligence WCCI1994,* Vol. 2, pp. 1263-1268

Rossi, F.; van Beek, P. & WALSH T. 2006. Handbook of Constraint Programming, *Elsevier, Amsterdam*

Sauer, J. 1998. A Multi-Site Scheduling System. *Proc. Artificial Intelligence and Manufacturing – Research Planning Workshop*, Albuquerque, AAAI-Press, pp. 161-168

Slany, W. 1994 (?). Scheduling as a fuzzy multiple criteria optimization problem. Technical Report 94-62, TU Vienna