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QUALITY MANAGEMENT IN THE PHASE OF CONSTRUCTION EXECUTION BASED ON BUILDING INFORMATION MODEL-A REVIEW

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ABSTRACT

The construction industry is an important economic sector. But losses according to produced defects during the construction execution are enormous. The digitalisation in the construction industry is growing and has a great potential to improve execution. By now, digital methods like BIM are primarily used in the planning phase. In the construction execution, especially in the management of qualities are analogous or document-oriented systems state of the art. These systems usually focus on the management and correction of defects. The monitoring of construction quality, including the prevention or detection of defects, is neglected. The following paper will overview past and current research activities in quality management in construction execution by a systematic literature review. This review enables further research and improves research activities lasting.

INTRODUCTION

Problem definition

Quality problems are an accepted part of the construction execution. Multiple insurances publish reports about the negative trend of construction quality. A study by the Institute for Building Research shows that between 2009 and 2016, 89% more defects occur in one-and two-family houses in Germany (Helmbrecht et al. 2018). According to a report by the VHV (Vereinigte Hannoversche Versicherung) insurance, 70 % of the insured events can be traced back to the execution of construction work, and only 10% of the damages can be attributed to planning services. (Böhmer H. et al. 2020). The insurance company Allianz AG also publish that defect construction products and missing or insufficient quality controls are the most frequent source of building damages (Allianz AG 2019). These examples show that the construction industry is far from error-free construction production.

On the other hand, digitalisation in the construction industry increases continuously. Especially the usage of digital information models like building information models (BIM) has grown. By now, the usage of digital methods is focused on the planning and utilisation phase. Roland Berger's survey investigates a missing awareness of the importance of digital data, access and connectivity in the production phase and quality management of construction projects (Berger 2016). It becomes clear that digital information models have the possibility to improve quality management in the execution (Chen und Luo 2014). But these methods are not commonly used in the construction execution or are usually limited to the company itself.

This leads us to the following reason for quality issues. The construction industry is fragmented, and construction companies operate in information silos (Zhong et. al. 2012). The isolation results in missing or erroneous communication, higher effort in information acquisition as well as defect. In the case of quality, information silos indicate missing product and process requirements exchange and defect prevention, determination, communication as well as solving.

To achieve better quality management, it is necessary to leverage the project level's point of view. Due to the fact that the overall quality is the sum of all qualities delivered by the construction companies and suppliers. It is necessary to implement a data model for quality-related stakeholder of a project to break down information silos and connect information over multiple project participants according to quality. To achieve this, the project participants must connect quality-related information over multiple construction domains like BIM, schedules, machinery data, site documentation or regulations (Marsden 2019). In addition, this kind of system will break down information silos (Lee et al. 2016). It will also increase the transparency between the project participant and increase quality, the trust of subsequent work, and the customer's approval.

This paper aims to analyse the current state of digital and project-related quality management in the construction execution phase. The focus is on information systems that distribute quality-related information. We will not handle methods of defect recognition on the construction site. For the recognition, it is of interest how data are stored and used in the quality-related information's systems.

Project-related construction quality management

According to Bach and Bargstädt controlling can be seen as the triangle out of time, cost and quality.

During the project, the importance of time, cost and quality for the owner will change continuously. In the phase of execution, time and quality are essential, and quality and cost become the most important factors in the handover.

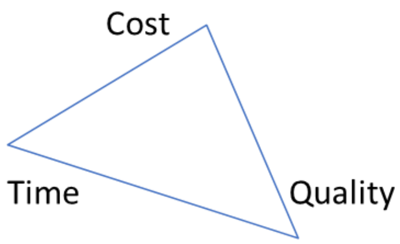

Figure 1: Trias of cost, time and quality

All three criteria have to be in the right balance during the whole project. Comparing the three factors, quality is the criteria with the wide-rangest impact (Bauch und Bargstädt 2020).
Quality represents the divergence between desired properties and the actual properties of a product. According to DIN EN ISO 9000:2015 11, quality is understood to be the "degree to which a set of inherent characteristics of an object fulfils requirements". Costumer, companies, or authorities can specify the requirements. Requirements are based on specification, standards, norms, administrative orders, or individual customer and company requirements (Girmscheid 2014). The quality can be divided into the product- and process-related quality. The process quality aims to prevent defects and to assure quality. The output results from the sum of processes and can be a product or a service (Helmus und Offergeld 2012). The product quality is, therefore, the result of the process quality. If all requirements are met during the process, the product quality will be high. In other words, a high process quality results in high product quality (Girmscheid 2014).
Quality management serves the management of quality and is divided into the four areas of 1) quality planning, 2) quality assurance, 3) quality control, and 4) quality improvement (DIN EN ISO 9000:2015 11). The construction quality describes the fulfilment of the building compared to a described condition. The paper focuses on project quality management (PQM) for the construction execution phase. The PQM is focussing on meeting the client requirements during the project. The QM-Concept, including the QM-Plan, will determine the client's processes, responsibilities, or actions to meet the project requirements and control quality during the construction execution (Girmscheid 2014).
During the project construction managers and other project participants need to recognise negative trends like defects or quality problems as soon as. This enables the controlling to take action against the trend and minimise the negative impacts on the whole project (see Figure 1). Controlling actions like target-actual comparison have to be done punctually and interpreted according to the final project stage (Berner et al. 2009). Controlling activities must be done by self-monitoring or external monitoring. External monitoring can be done by third party inspections or customer-oriented inspections (Kim et al. 2008). These can be authorities, laboratories, auditors and other instances. Especially construction material like concrete with high exposure classes requires external monitoring by laboratories (DIN 1045-2). A further controlling mechanism on the construction site is controlling by subsequent works. These have to check the work of the preceded discipline because they want to continue on the prework. Because controlling is a multi-participant task for all project stakeholders, team-based and transparent quality controls are necessary to assure and achieve required product qualities.

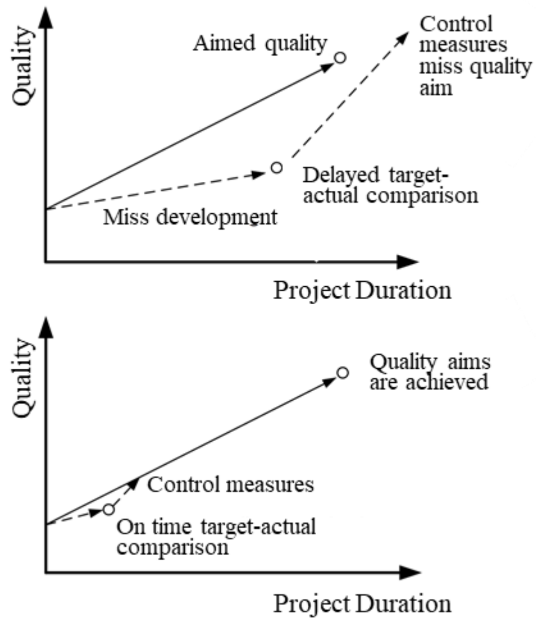

Figure 2: Effects of delayed and timely quality control measures adapted from (Berner et al. 2009)

Semantic model and rule checking

The basis for understanding quality management systems is the grasp of the method of compliance checking. The compliance checking, especially in rule checking, can be described in two layers (see Figure 3) (Pauwels und Zhang 2015).
The first layer is represented as the semantic model. The semantic model is based on a schema or concept, which defines the contained objects, relations and properties. The schema follows mostly a class hierarchy and builds up relations between different classes. In addition to the semantic model, also instances are necessary to do quality-related checks. Instances are objects representing a real-world statement of a class according to the schema in the semantic model (Staud 2015).

The second layer is represented as the rule layer, and it is responsible for checking or planning quality-related

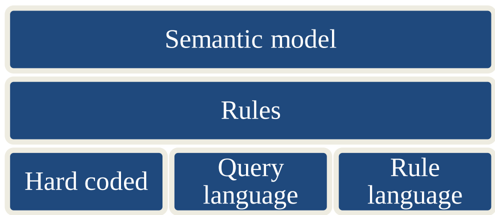

Figure 3: Interaction semantic model and rules

controls. The rule implementation can be done as 1) hard-coded, 2) querying or 3) rule language. Each of these implementations has its strengths and weaknesses (P. Pauwels und S. Zhang 2015). For instance, hardcoded rules are like a black box and cannot be easily understood by non-experts or are mostly hidden for the user. On the other way, queries and rule languages are more or less white-boxes. This means that non-experts can understand the content of the rule. So the user knows what and how the rule is working. Figure 4 illustrates the principle of a white- and black-box implementation of rules (Borrmann et al. 2018).

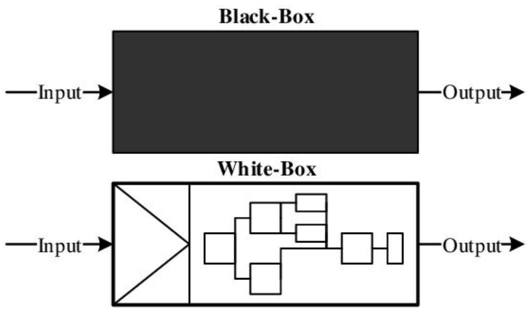

Figure 4: Black-Box and White-Box methodology for rule implementation (Borrmann et al. 2018)

Further interesting is the process of compliance checking. The process of checking is based on the translation of rules in a machine-readable language. Based on this, the rule's execution can be done concerning the instances of the schema for quality information. Finally, the results of rules execution, in our case, the quality checking or planning, have to be represented. This process is illustrated in Figure 5, adapted from Eastman et al.

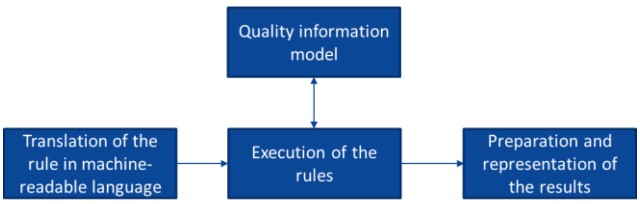

Figure 5: Process of quality compliance checking adapted from (Eastman et al. 2009)

Quality information model

The described interaction between a schema and defined rules has now specified to project-related quality management in the construction execution. The quality information model will share all quality-related information between the project participants. According to Marsden, digital quality information models have to handle four information elements: people, materials, processes, and machines. Controlling these topics by information management, the overall performance can be optimised (see Figure 6) (Marsden 2019).

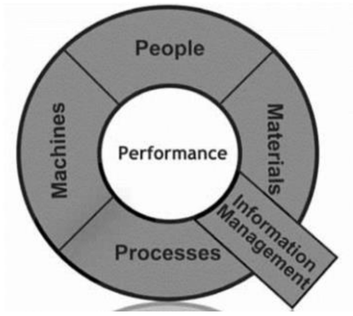

Figure 6: Four elements of a digital quality management model (Marsden 2019)

Figure 6 illustrates that the self's quality depends on many different domains and can not be seen as a closed environment. Without the different domains included in a quality information model, it will not be possible to evaluate and control quality properly. Marsden writes that the quality information model will be the foundation for rule-based quality assurance and quality control.

By now, information system in the construction industry focus on the description of the construction. The BIM methodology's further development increases information exchange formats for the digital building model like Industry Foundation Classes (IFC). Information models for the construction execution are not standard and are limited to the cost and time implementation into the BIM. Also, the exchange of problems and issues is standardised for the planning phase by bim collaboration format (BCF) but not for the execution phase.

METHODOLOGY AND SCOPE

As research methodology, a systematic literature review is chosen. The review will provide an overview of the research question:

> How to improve the project-related quality of the construction execution by digital process and quality information models?

The paper will outline research activities for quality management in the construction execution using product and process models, like building information models. The construction execution is including the two process steps 1) work preparation and 2) work execution, which is relevant in the project-related quality management system. Therefore, we describe the process steps of quality management in the construction execution (See Figure 6). The process for quality management in the execution phase is defined by work preparation (blue) and execution (red). Single activities illustrate the process steps of each phase. The process steps quality record to control measures can be seen as a Plan-do-check-act-(PDCA) cycle, which must be repeated until the quality is according to the requirements or the quality is accepted.

In addition to the categorisation, the current state of knowledge, as well as research gaps, are revealed. The research is limited to the last ten years' research activities and databases of the journal archive of Elsevier, Taylor &

Francis, and Google Scholar, ResearchGate and SpringerLink.
The abstracts of the papers were used to categorise the articles according to the research question, which was supported by an in-depth literature analysis. References in the literature were also taken into account.

RESULTS

The following chapters represent the research results. First, an overview of current research activities is given. Further analysis is done based on the overview, according to the deducted categories of processual view, quality model implementation, and rule implementation.

Overview

Based on the literature review, we could find 13 relevant research papers. The papers are structured according to the process category and the research focus in Table 1. Most research activities, according to construction quality, are made in eastern Asia. Mainly research institutes in the field of construction management focus on quality management.
All in all, 9 of the 13 published papers are written by authors in China and two by authors in Korea. We conclude that quality control and assurance is mainly focused on Asian countries. The research activities also changed over the years. In the year 2018 occurred higher research activities than in the years before.
It becomes clear that the research on quality management in construction execution is limited. The rare research activities on quality management could be based on limited warranties for construction products as well as the lack of customer loyalty associated with one-off production.

Processual view

The following research is described in a procedural view of quality management and the implementation of the quality management systems in the process. As a result of the study, the paper's primary focus is related to the execution phase. Rear papers handle the work preparation phase. This becomes clear by the list of publications in both areas. The execution phase is handled by 12, and the work preparation is handled by 4.

Work preparation

The phase of work preparation is handled related to the process of planning quality controls. Martinez et al. describe an ontology-based model in their paper that can select and connect information of standards of Quality Control Specifications based on BIM. The developed ontology model consists of three main modules representing the product, i. e. construction-oriented product ontology, manufacturing-oriented product ontology and quality control ontology. In order to populate ontology with BIM data, the ontology model is saved into RDF file (Martinez et al. 2019).
Zhong et al. (2012) developed a quality management system, including control planning and quality compliance checking. Control planning includes the axioms which quality controls have to be done according to which process steps. The axioms will create new instances for controls that can be used or support the site engineer to check all required quality regulations. The paper does not present implementation on who, when and with which methods (Zhong et al. 2012).
Chen and Luo (2014) give another approach. In his concept, he develops a 4D-BIM based quality management system. The 4D-BIM is used to identify quality control criteria and to investigate responsibility requirements (Chen and Luo 2014). Also, Ma and Chai derive inspection task by an IFC model and a hard-coded algorithm. The system-based inspection task planning method reduced the time for inspection task planning to 1/8. This paper shows directly that significant improvement can be achieved in the work preparation phase (Ma et al. 2018).
The whole literature treats the predictive problem analysis inadequately. The planning of quality controls is done in different approaches like described before. The implementation of quality control planning is directly related to quality recognition and quality compliance checking. None of the papers fulfils the requirements on planning quality controls by who, how, which, what quality controls have to be done. By now, no research activity joined the different approaches to define quality checks in detail.

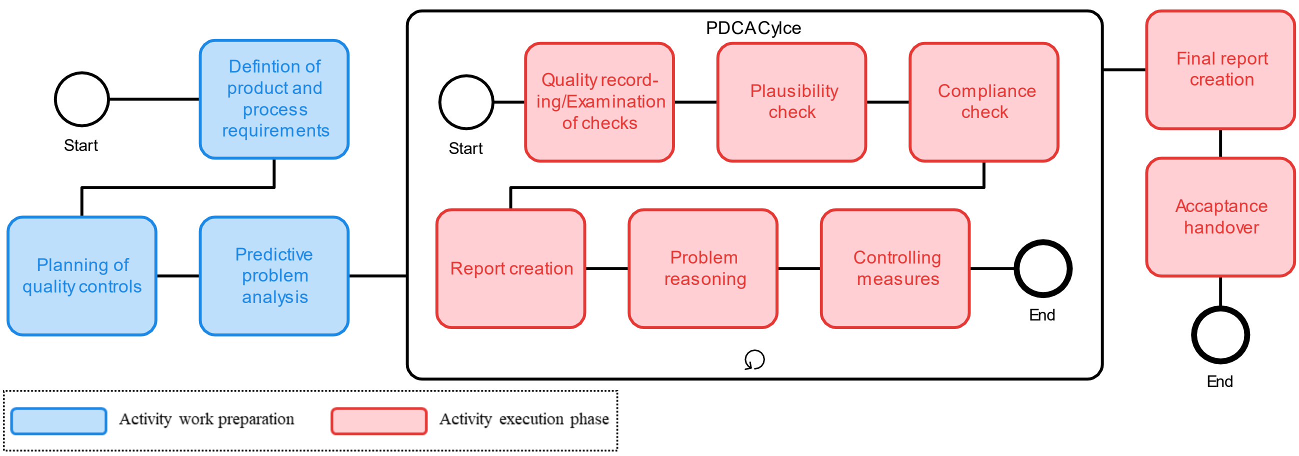

Figure 6: Process diagram of quality management in the construction execution phase

Table 1: Overview of relevant research paper (Process: E-Execution phase, W-Workpreparation)

No	Name of the paper	Year	Autors	Pro-cess	Research focus
1	Developing an IFC-Based Database for Construction Quality Evaluation	2018	Xu, Zhao; Huang, Ting; Li, Bingjing; Li, Heng; Li, Qiming	E	Evaluation of quality-related data by an IFC-based relational database, extended by quality data and a neural network. The evaluation is not performed on a single defect but on the entire project.
2	Application of BIM on Documenting Construction Defects	2018	Cheng, Ying-Mei	E	Development of a tool in Revit for quality recording and compliance checking.
3	Building Information Modeling for Quality Management	2018	Cheng, Ying-Mei	E	Focus on checking mobile recorded quality data. Usage of Revit API and Access to store and check quality.
4	Integrating BIM and LiDAR for Real-Time Construction Quality Control	2014	Wang, Jun; Sun, Weizhuo; Shou, Wenchi	E	Recording and evaluation of drone data in relation to product quality. Limited to geometrical control of quality.
5	Developing construction defect management system using BIM technology in quality inspection	2016	Lin, Yu-Cheng.; Chang, Jun-Xiong; Su, Yu-Chih	E	Development of a defect management system on a web-based portal for mobile application. Defect recognition and manual checking on and off-site.
6	A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template	2013	Park, Chan-Sik; Lee, Do-Yeop; Kwon, Oh-Seong; Wang, Xiangyu	E	Proactiv defect and quality management tool, System is based on an ontology and saves defects by a template. Also, AR is used to support inspections and to check defect corrections.
7	A linked data system framework for sharing construction defect information using ontologies and BIM environments	2016	Lee, Do-Yeop; Chi, Hung-lin; Wang, Jun; Wang, Xiangyu; Park, Chan-Sik	E	Develop an ontology for quality management, integrating BIM to store and check recognised qualities on the construction site against SPARQL Queries requirements.
8	Ontology-Based Approach for Automated Quality Compliance Checking against Regulation in Metro Construction Project	2012	B.T. Zhong, H.B. Luo, Y.Z. Hu, and J. Sun	W, E	Implementation of a quality inspection system based on an ontology, as mentioned above. The similar implementation is done to another project.
9	Ontology-based semantic modelling of regulation constraint for automated construction quality compliance checking	2012	Zhong, B. T.; Ding, L. Y.; Luo, H. B.; Zhou, Y.; Hu, Y. Z.; Hu, H. M.	W, E	Definition of a quality ontology to plan store and check quality-related inspection. The SWRL rule language does the compliance checking of recorded inspection data. The model does not include BIM or specifications.
10	A Web-Based BIM–AR Quality Management System for Structural Elements	2019	Mirshokraei, Mehrdad; Gaetani, Carlo Iapige de; Migliaccio, Federica	E	Using a 4D and IFC BIM to derive requirements, time, responsibilities for control activities. Quality data is stored in a relational database. AR do the quality checks, and the results are linked to the database. Checking and evaluation are done manually.
11	A BIM-based construction quality management model and its applications	2014	Chen, LiJuan; Luo, Hanbin	W, E	Quality management system combines a 4D model with a company's POP (process, organisation & product) model to improve communication for defect elimination. Inspection templates are linked to BIM, completed by on-site da and checked manually.
12	Construction quality management based on a collaborative system using BIM and indoor positioning	2018	Ma, Zhiliang; Cai, Shiyao; Mao, Na; Yang, Qiliang; Feng, Junguo; Wang, Pengyi	W, E	Development of quality-related collaboration system in combination with indoor positioning. Algorithms generate inspections task; inspections are visually supported by a positioning system. Visualisation of inspection results by bubbles, Manuel check and interpretation of inspection results.
13	Automatic Selection Tool of Quality Control Specifications for Off-site Construction Manufacturing Products: A BIM-based Ontology Model Approach	2019	Martinez, Pablo; Ahmad, Rafiq; Al-Hussein, Mohamed	W	The Ontology selects automatically quality control specifications of companies or organisation according to the requirements defined in the BIM. SPARQL queries derive the standards.

Execution phase

The quality management systems considered publications focus mainly on the three processes of quality recording compliance checks and report creation. A different approach like scans does the recording of data with drones (Jun et al. 2014), mobile end devices including augmented reality applications (Li et al. 2016, Mirshokraei et al. 2019) (Park et al. 2013) or indoor positioning (Ma et al. 2018). In addition to recording quality-related data, the storage in a data model is handled by all papers related to the phase of construction execution. Further information about "how quality-related data is stored" will be discussed in the following chapter. The other process step in the reviewed papers is the check for quality compliance with regulations or the BIM. This step is done manually or automatically by executing rules. The manual approaches use predefined checking templates and the BIM product requirements to evaluate the user's quality. Also, it is possible to use the proposed systems for manual problem reasoning and define control measures. The monitoring and visualisation of quality problems are not further considered in this literature review.

The approaches, including BIM, aim to track defects and the compliance checking of quality related to the BIM information. If the given alphanumeric information, also denoted as Level of Information or the geometrical detail denoted as Level of Detail of a BIM is insufficient, the recording of defects is impossible (Lin et al. 2016). So, it becomes essential to describe the necessary data of quality assurance and control in BIM exchange requirements.

In addition, we found a lack of knowledge in the execution phase; the papers do not handle the process step of plausibility check. The plausibility will allow the system if monitoring results of the construction site are realistic to monitor. Furthermore, the analysis has shown that processes for solving problems or controlling measures and determining the causes of quality problems were not dealt with in the papers. Thus, when a deviation is possible, systems can identify where or what caused the problems. An example from the concreting process is the formation of gravel pockets in a wall. There are different reasons for gravel pockets. One cause could be incorrect compaction of the concrete; these deviations could be specified more precisely using process data and product data. Based on the identified defects as well as causes, the project participants can propose control measures punctual. Such knowledge-based processes represent enormous potential and development opportunities in the field of quality management.

Also, a general focus on multiple projects is missing. None of the research papers postpones a quality management system that can save defects, reasons, and solutions for multiple projects and use this information for further analyses. So, past projects' knowledge is not used to do predictive analyses and break down knowledge silos. All in all, we can determine that the execution phase is further developed/more research done than the work preparation phase.

Quality model implementation

The analyses of the quality models' implementation are done in two approaches 1) relational databases and 2) ontologies. In this review, five of the 13 papers have used ontologies and the other relational data models. All created quality management systems are unique and were created for the respective paper. There are differences in each of these data models due to the different thematic focus of the papers. Differences occur related to if and how standards, product and process requirements, inspection and monitoring data are stored and related.

Basically, the model shown in Figure 7 can be considered as a basic model of quality management systems in construction. The model is based on four domains 1) the product requirements describe the construction for example, by a BIM or the requirements according to materials, 2) the process requirements are described according to the task like time constraints, machine requirements or worker requirements, 3) the quality recording describe the information retrieved by the construction site, 4) the quality evaluation describes the standards or specification, which are used to evaluate recorded inspection data against requirements. In each observed system is the minimum one of the requirements and one of the other two domains implemented. Therefore, not all domains have to be implemented to call about quality information system. For example, (Martinez et al. 2019) implemented standards related to product requirements. The most implemented domains are the product requirements and the Site information domain.

In the papers of Mirshokraei M. (2019), Xu Z. (2018), and Chen L. (2014) is the IFC added by the quality management domain and implemented in a relational database. This approach has the advantage that the product model and process model are already defined and used for further approaches. It proves advantageous to include quality-related data in the IFC, especially for the construction execution. Other applications proposed in the papers directly use the internal product models of the systems like Revit and extend the tools by quality-related function data models.

An issue of the ontology approaches is the missing usage of predefined ontologies or other usable ontologies like

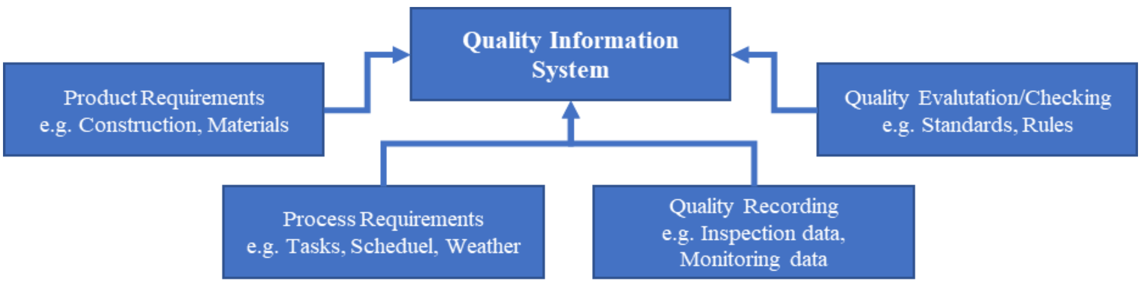

Figure 7: Related domains of quality management systems

the Industry Foundation Classes Web Ontology Language ifcOWL. Other possible construction-related ontologies are the Digital Construction Ontologies (DICO), Semantic Sensor Network Ontology (SSN) and the defined ontology of Zhong et al. (2012). Also, the opportunity to link monitoring data to ontologies is not used. However, linked-data methods can fix interoperability issues in the construction execution and break down data silos (Pauwels et al. 2017). Monitoring data are highly dynamic and can be reported by various sources. We should further investigate the exchange of information between the monitoring systems and quality management systems. Besides, further investigations are necessary to evaluate how monitoring data of the construction site is exchanged between the systems?

Rule implementation

The quality standards and criteria are implemented in three ways: 1) hard-coded, 2) queries, or 3) rule languages. A problem mentioned by Chen and Luo is that quality criteria focus on national, industrial and local quality control codes for construction (Chen and Luo 2014). They recommended defining rules in a user friendly and white-box approach, enabling non-experts to implement rules in the system.

Most of the research papers used hard-coded rules implemented directly in the application and cannot be understood by the user. Other researchers like Lee et al. (2016) and Martinez et al. (2019) used the query language SPARQL to query specifications or check for compliance. A rule language is just applied by Zhong et al. (2012). Zhong used the rules for quality checking and inspections planning, e. g. if a process task is defined, also an inspections task has to be defined.

In the reviewed research papers, three focus on rules according to grouting foundations, in compliance with the norm GB50202-2009. Also, technical quality standards against general concrete work are common in the research papers. Quality checking, according to earthwork or craftsman specific tasks like electricity or plumping, are missing.

The rules' execution to check tracked information and prepare controls or reason problems depend hardly on the information proposed by the BIM. Building parts not described by a building information model cannot be used as quality control requirements. An example is temporary elements, like Formwork, scaffolding. These elements are necessary for the construction process quality are not provided by design-oriented BIM (Chen and Luo 2014).

CONCLUSION

The literature overview illustrates different variants of the implementation of a quality management system for the construction execution. The variants of implementation can be structured according to the information model, the applied rules, and the process steps these management systems focus on.

We have demonstrated that many solutions are emerging, and especially new monitoring procedures for defects have been implemented together with an individual information model. However, the constant development of new data models for quality management is a waste of research activities. A way has to be found to provide a data model representing a master data model on which the participants can build new monitoring models upon.

The standard method to implement a quality system was to use BIM as IFC and connect the model by a graphical user interface (GUI) with a relational database. The database contains quality-related information like standards or reports.

The presented paper provides a research background for the subsequent studies to develop a new conceptual model for a project-related quality management system. It becomes clear that further developments in the planning of quality controls, predictive quality problem analysis, plausibility checking, reasoning, and quality measures have to be done. Following research activities have to focus on these process steps. Especially the usage of quality-related data over multiple projects and multiple project participants can improve predictive quality analyses, controlling measures and generally the view on quality. This will turn the current, mainly reactive quality management into proactive quality management. Furthermore, quality management must leave the company's point of view and be applied to the whole project and its participants to share information and improve communication.

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