Report on DiCtion WP D
Engineer-to-order supply chains and logistics processes
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1 Introduction

The management of supply chains is problematic in construction. Challenges are due to the discontinuity of demand for projects, the uniqueness of each project in technical, financial, and socio-political terms, and the complexity of each project in terms of the number of actors involved. In construction, the logic of SCM typically does not follow any single known method of production as the supply-chain often connects industrial factory production with on-site assembly and customization.

The current project management dominated view on the construction supply chain is insufficient for maximizing customer value, eliminating time and resource waste in material processes, and automating the logistic system. Digital workflows would promote automation in supply chain management. However, there is a lack of research about how to manage workflows digitally and how to integrate material flow management efficiently and effectively with assembly workflow happening on site. New methods are needed to integrate all information about supply chain and its capacity and capability already in the construction planning phase and use that information intelligently when managing construction workflows and supply chain operations as a one integrated production system.

Successful construction supply chain management necessitates digital workflows. Digital workflows allow, e.g., advanced material logistics and the management of ETO products. The digitalization of construction workflows has only recently begun, and lots need to be still done. This report discusses seven use cases for supporting digital supply chain management. Kitting logistics process provides requirements for digitalization.

This report presents the results received in work package D (WPD) of DiCtion (Digitalizing Contruction Workflows) research project. WPD work consists of three research streams, which all relate to creating a digital situation picture of construction workflows[1]:

PART I. Digital workflows for supply chain management (Chapter 2) which concentrates on engineer-to-order (ETO) products. This work has been more thoroughly reported in a conference paper[2].

PART II. Digital data flows in logistics (Chapter 3) which concentrates on make-to-stock (MTO) products. This work will be reported in two different scientific publications[3].

PART III. Requirements for inter-organizational deviation management process and system (Chapter 4). This work will be presented in a scientific paper[4].

PART IV. Company results of the Diction consortium related to the WPD (Chapter 5).

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[1] Kärkkäinen, R., Lavikka, R., Seppänen, O. and Peltokorpi, A. (2019), "Situation Picture Through Construction Information Management", Lill, I. and Witt, E. (Ed.) 10th Nordic Conference on Construction Economics and Organization (Emerald Reach Proceedings Series, Vol. 2), Emerald Publishing Limited, pp. 155-161.

[2] Lavikka, R., Lahdenperä, P., Kiviniemi, M. and Peltokorpi, A. (2021), "Digital Situation Picture in Construction – Case of Prefabricated Structural Elements", in Santos, E.T. and Scheer, S. (Eds.),Proceedings of the 18th International Conference on Computing in Civil and Building Engineering, Lecture Notes in Civil Engineering, Springer, Cham, Vol. 98, pp. 943–958.

[3] 1) Tetik, Peltokorpi, Seppänen, Holmström. "From Amateur to Excellence: Maturity Levels of Industrial Logistics Practices in Construction Projects", in progress, to be submitted to International Journal of Operations and Production Management.
2) Khajavi, Tetik, Mohite, Holmström, Peltokorpi. "Additive manufacturing in construction industry: feasibility of supply chain configurations", in progress, to be submitted to Automation in Construction.

[4] Lahdenperä, P., Peltokorpi, A., Lavikka, R. and Kiviniemi, M. "Improving quality in construction through a digital footprint: a case of structural elements", in progress, to be submitted to Automation in Construction.

2 Digital workflows for supply chain management

2.1 The need for digital workflows in supply chain management

Currently, the quality, scope and accessibility of data from construction operations are poor, which leads to inefficient construction supply chain management. We studied how digitalization could help in improving this situation. We focused on the supply chain management of prefabricated structural elements, which are engineered-to-order (ETO) products. The specification of ETO products is often challenging, the cost of these products is high, and the products are delivered in quite small batches to the site. These characteristics provide uncertainties to the management of these products. However, the uncertainty could be better managed through digital workflows that would allow transparency of operations.

Digital workflows would enable all project parties to know the up-to-date status of the construction site and better forecast into the future activities (Figure 1). For example, a better situation picture would allow understanding whether a need exists to adjust plans due to actualized deviations.

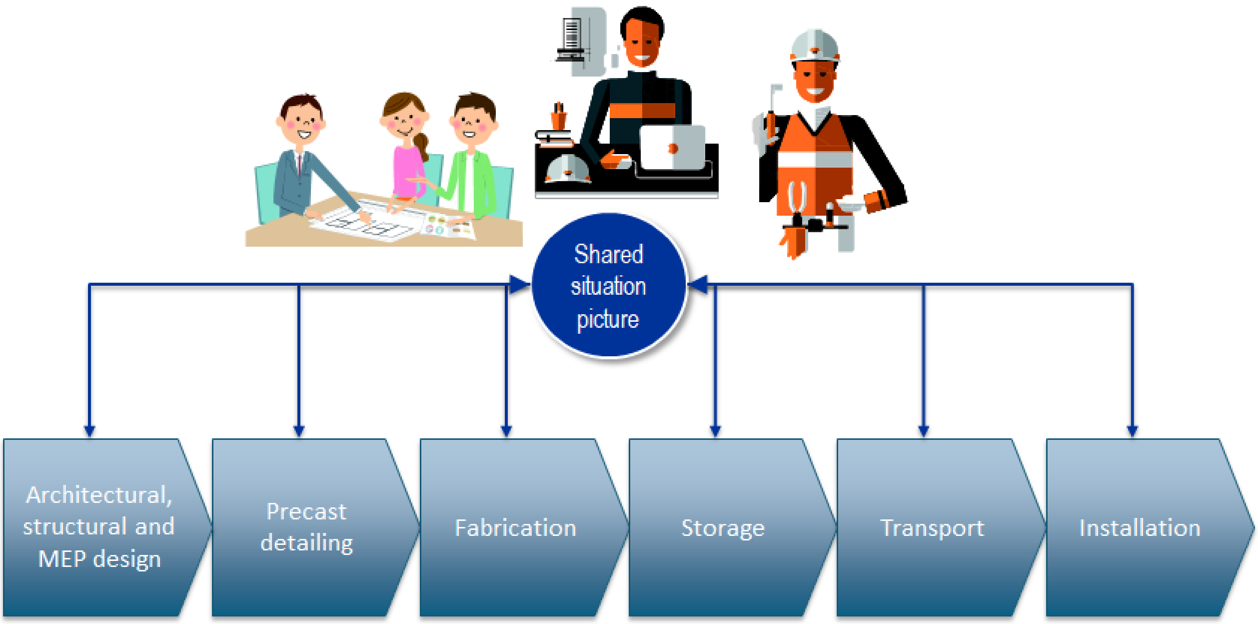

Figure 1. Shared situation picture allows better forecasting

2.2 Seven use cases for supporting digital supply chain management

Our study reports seven use cases, including the needed inter-company data flows, to support efficient supply chain management of prefabricated structural elements. These use cases are the following (Figure 2):

1) Optimisation of the schedule of designing and producing elements

The element fabricator manages production at granular planning level by dividing the full delivery by expected installation blocks at the site and collecting the installation timing data from the master schedule. Based on these data, the fabricator can optimise the schedule of designing and producing the elements in the multi-project fabrication environment. In the best scenario, there would be just-in-time production planning at the factory.

2) Optimisation of the look-ahead planning

The contractor needs from the fabricator the data concerning the status of the elements to optimise the look-ahead planning. These data are critical for the site managers as they plan their site production schedule.

3) Planning of the shipment of elements in transportation

The fabricator needs to receive data concerning the installation order of elements in planned blocks from the contractor. Based on these data, the fabricator can better plan the shipment of the elements for transportation.

4) Delivery capacity confirmation

The contractor needs to receive element status data from the fabricator to confirm delivery capacity on time to keep the project schedule. On the other hand, the fabricator needs look-ahead planning data from the contractor to forecast when transportation capacity is needed.

5) Planning of subsequent shipments

The fabricator needs to receive data on the realised installations from the assembly contractor for synchronizing production and planning of subsequent shipments. The method for recording the used statuses needs to be standardised and system-independent because elements can come from multiple fabricators. Standardisation would allow the supply chain data to be analysed and distributed automatically and transparently.

6) Standardised transportation management

The parties need a standardised transportation order method. Transport orders and receipts should be handled digitally to allow a better digital SP of the elements' statuses during transportation.

7) Issue management

Contractors' issues and reclamations concerning the elements should be handled digitally and be shared with other companies when necessary. The digitalisation of issue management would enable learning from mistakes and avoiding them in the future as well as facilitating the commercial procedures between the parties.

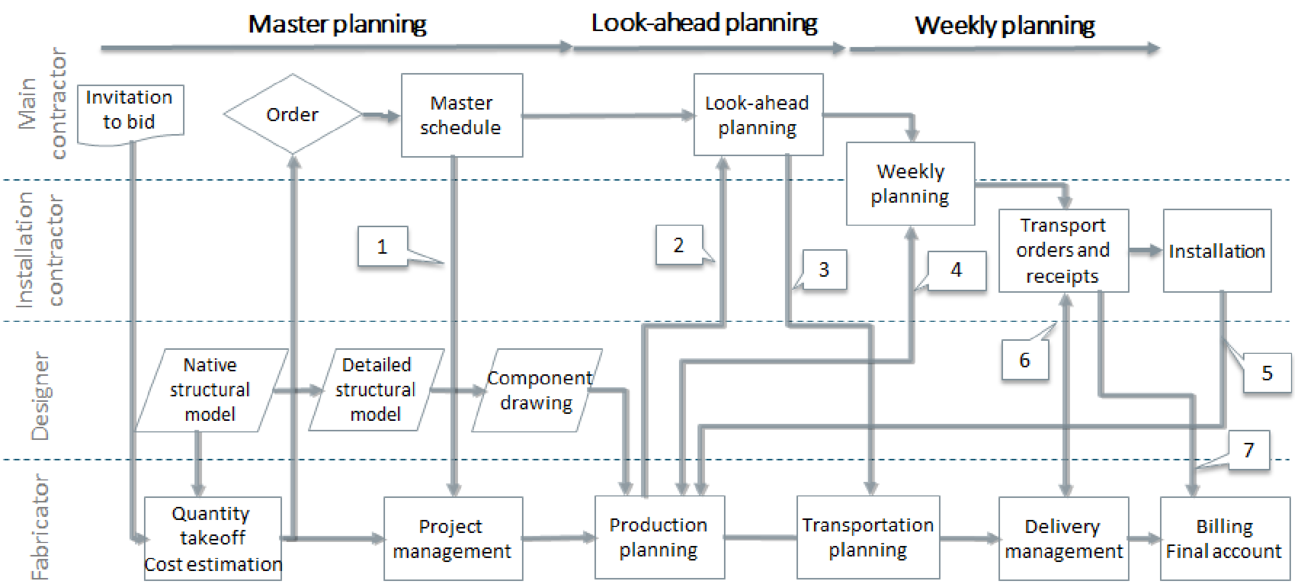

Figure 2. Digital dataflows of the seven use cases. (adopted from Lavikka et al. 2021[5])

These use cases necessitate that specific data, such as – the identification number of a prefabricated structural element, installation blocks, installation order and its schedule, transport loads and their orders and element statuses – are shared in a digital format. The identification number should be shared in a generic format agreed by all fabricators. Digital workflows support efficient supply chain management, which could lead to optimizing productivity in the form of reduced costs and duration and improved construction worker safety on-site. Also, a low level of inventories and the elimination of waste in the form of rework and unnecessary transport operations could be achieved by efficient supply chain management.

3 Digital data flows in logistics

3.1 The need for advanced material logistics

Advanced material logistics solutions are increasingly important to increase supply chain efficiency and assembly work productivity in construction projects. Material kitting represents one logistics solution which is becoming more popular in engineering projects. However, to be efficiently adopted, it requires appropriate information flow and digitalized workflows.

3.2 The kitting logistics process

The kitting logistics process involves the process of material delivery, kits preparing/assembling at the logistics centre, kits transporting, on-site unloading and distributing (shown in Figure 3). First, the material batches are delivered to the logistic centre by suppliers. Then the workers in the logistic centre should follow the material bill that indicates the required constituent material types in each assembly task and the quantity of the materials to prepare the kits. After the preparation, the kits are assembled as groups/packages of

[5] Lavikka, R., Lahdenperä, P., Kiviniemi, M. and Peltokorpi, A. (2021), “Digital Situation Picture in Construction – Case of Prefabricated Structural Elements”, in Santos, E.T. and Scheer, S. (Eds.),Proceedings of the 18th International Conference on Computing in Civil and Building Engineering, Lecture Notes in Civil Engineering, Springer, Cham, Vol. 98, pp. 943–958.

these materials and ready to be shipped to the construction site with a short lead time. These kits are typically location-based (provide the materials for designated location), task-based (for the designated task), and time-based so that they can contain, e.g. all materials needed in working two days in a renovated bathroom.

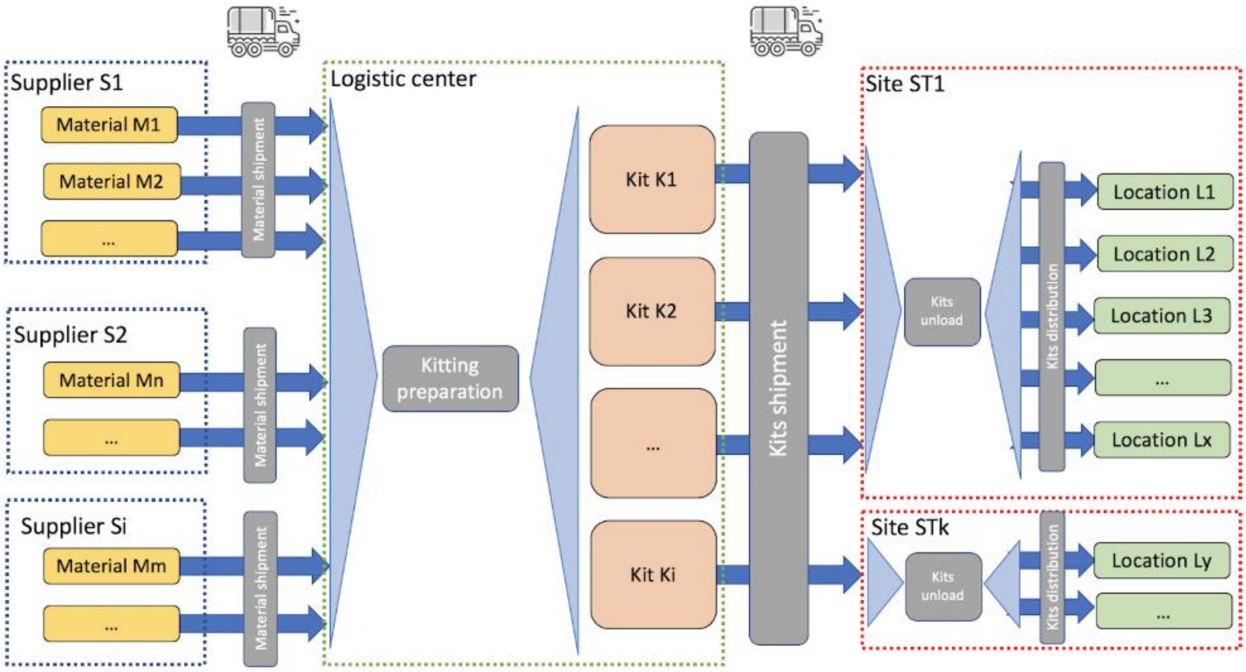

Figure 3. The kitting logistics process

At the designated time, typically around one day before the corresponding task will start, the kits will be delivered to the site. This delivery time is determined by the progress of the construction, which also applies a Just-In-Time (JIT) delivery method for the following operations on the site. When the kits are delivered to the site, they will be unloaded and distributed to the required locations for corresponding tasks. Kitting increases work productivity and workflow stability as it reduces the logistic work of professional workers and enforces workers to follow the planned schedule and restrict workers moving to another work location. It also decreases interruptions and material waste. Kitting can also enable pre-assembly of components and materials in the logistics centre, further improving work productivity.

3.3 Requirements for digitalization: Kitting logistics process

To work properly, kitting sets some requirements for information management and its digitalization. Figure 4 presents the major elements of the kitting management system and their interrelations. First, the digital design of the building, including its elements and spaces, should be utilized when defining the bill of materials (BoM) for different tasks in each location. This requires that commercial products which have been purchased by general or trade contractor should be linked to the elements of the digital building model. This element- and space-based BoM information combined with the digital planning information about element- and space-linked tasks would enable defining assembly kits with the specific bill of materials, their schedule and location. Regarding location information, three space elements are important: a) space into which the kitted material will be installed, b) workspace which the worker needs to use during the assembly task, and c) space for materials in or next to the workspace. For example, in tiling work of a bathroom, installation space and workspace are often one and the same, the whole bathroom. Instead, space for materials should be found typically outside the bathroom.

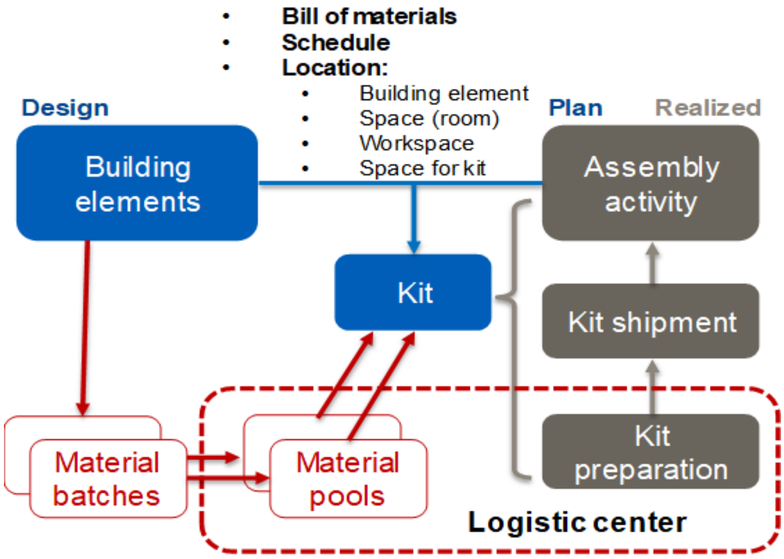

Figure 4. Requirements for digitalization: the kitting logistics process.

From a material point of view, it is important to enable digital management of logistic centre's inventory levels and activities. Similar materials required in the project represent a material batch of which some subset (=pool) is ordered at a time to the logistic centre. Levels of these material pools, as well as prepared kits, should be controlled and shared among project parties. Kit preparation, shipment and final assembly on-site form a set of coordinated activities. In the end, digital registration of the realized assembly activity of one kit may redefine preparation, shipment and assembly plans for the following kits in the same or other locations in the buildings. This dynamic production information should be shared in real-time with the relevant actors and trades in the project. Sharing information about additional and waste material of kits enables learning on accurate bill-of-materials inside the project if there is repetition in the tasks and consecutive kits. Similarly, collected data enables learning from project-to-project in kit definition, preparation and optimal delivery time.

4 Requirements for inter-organizational deviation management process and system

4.1 The need for inter-organisational learning

Construction projects often involve multiple organizations working in temporary settings. Each organization, such as design office, element fabricator and general contractor, typically focuses their quality activities in one part of the project using intra-organizational quality policies, processes and information systems. This context creates a challenging starting point for project quality management, which is crucial for the success of a construction project.

Contracts are often used as quality management instruments between two organizations in the project. However, as projects are complex networks of organizations with multiple clients and supplier relationships, quality deviation issues, i.e., nonconformance, often involve more than only two project actors. Therefore, with current decentralized quality systems and contractual arrangements, it is hard to target deviation information to the root cause, especially in large construction projects. Many quality problems surface only during the construction phase and only when accuracy increases, such as when mounting prefabricated products that need to fit into a tiny spot. As a result, the industry is not learning together, and the same mistakes are made over and over again (Figure 5).

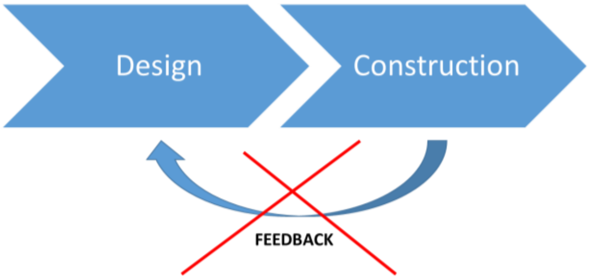

Figure 5. A feedback loop is missing, which prevents learning.

4.2 Deviation management as part of companies' quality management processes

Deviation management refers to the handling of a problem or an open issue, such as an RFI (request for information), punch list during the final inspection, or safety notices. A deviation can also be referred to as a reclamation. Companies consider deviation management to be an integral part of quality management procedures.

In general, companies follow quality management instructions during the project management phases - initiating, planning, executing, controlling, and closing (IPECC) - and apply ISO 9000 quality management system standards. Quality management processes aim at fulfilling quality requirements during the project, starting from tendering to archiving. Nowadays, several quality management systems exist on the market. In general, these systems allow the storing of documents, such as the project plan, guidelines and requirements documents in the cloud, so that every project member is able to access them easily.

Companies monitor external complaints and internal deviation findings and search for root causes in weekly meetings where meeting memos are produced. Some companies held annual quality assurance (QA) meetings between departments to share good and bad feedback and to learn from them. Still, the companies reported challenges in sharing the feedback to all relevant employees.

Companies send customer feedback surveys, some even automatically, at the end of the project. The survey results are provided to project managers who have to provide a short comment to the upper-management based on the feedback. Many companies apply Net Promoter Score (NPS) as a measure for quality and compare it with abroad units and other companies. NPS is the most widely used measure of customer loyalty internationally.

Companies emphasized that a good information management tool and planning ahead are the most important quality management activities to prevent deviations. Every worker is responsible for observing and in some companies, even reporting deviations. However, usually, the project managers are the ones reporting the deviations. Also, they tend to report only 'bigger' deviations. Table 1 summarizes the current practices in handling deviations and their strengths and weaknesses from the perspective of designer, fabricator and contractor.

Deviations are reported into a quality management system or in some cases into an Excel file. InstaAudit[6] is an example of a quality management tool for tracking deviations. These kinds of tools can track deviations in the process (cause-effect) and provide visualizations of the current situation in deviation management, such as a graph showing the percentage of problems on a weekly or yearly basis. Thus, the user can lead the deviation management process in a particular direction.

Companies seem to have general guidelines for reporting deviations. In general, when reporting a deviation, one needs to report the project number, clients, job numbers, description of the incident, immediate corrective actions, and later on the other corrective actions. The deviation needs to be linked to the closest deviation class, and any financial impact needs to be recorded.

In general, three classes of deviations exist: 1) project deviations, which can be for example design deviations, 2) process deviations, which deviate from quality requirements and 3) safety deviations, for example, if someone slips on a business trip. Project deviations are again divided into deficiencies in the source information, a shortcoming in the design, collaboration, lack of guidance, tools, human error, or other reason.

Deviation management also relates to work progress tracking, which is often done internally as well. For example, an element factory can track the lifecycle statuses of an element to determine whether the element can proceed to the next phase in the line. Examples of statuses are raw design ready, ready for production, produced, factory-ready, on-site, installed. Critical questions can be, for example, whether the dimensions are of the right size or whether the reinforcement is placed before casting permission can be given.

[6] http://instaaudit.com/fi/. InstaAudit is developed by Kiwa, formerly known as Inspecta.

Table 1. Current practices in handling deviations and their strengths and weaknesses from the perspective of designer, fabricator and contractor.

	Designer's perspective	Fabricator's perspective	Contractor's perspective
Current practices	• No firm-level measurements of deviations • In-house deviation management • The project manager reports 'bigger' deviations into the quality management system, and the quality manager gets notice of deviations. • The quality manager keeps track of the deviations in an Excel file. • Project feedback is shared in weekly project meetings and annual QA meetings between departments. • In the monthly quality newsletter, 'the deviation of the month' in a positive sense is shared to all employees.	• Deviations are handled professionally inside the company using deviation management software.	• The site workers are used to calling right away to the designer or fabricator when a problem occurs at the site.
Strengths	• Deviations inside the company are dealt well. • Positive tune in the word deviation.	• Deviations inside the company are dealt well. • A professional deviation management system is in use. Analyses are shown in a visual format.	• Deviations are held immediately.
Limitations	• Not all deviations are recorded, usually, the ones that cause additional problems and costs. Thus, limited learning from deviations. • Deviation information stays inside the departments and projects, so not all people learn from them. • An information system for quality deviations would improve running analysis on the deviations after the project (now in Excel). • Deviations are not shared with other project parties.	• Do not receive data regarding the quality of the elements during the assembly.	• As problems are dealt by phone, no digital trace is available later on for further analysis and learning from deviations.

4.3 An inter-organizational digital deviation management process and its benefits

Digital deviation management provides benefits to the individual worker, company and inter-company project. A digital trace makes it easier for the worker to remember and manage individual deviations. At the company level, digital deviation management enables efficiency and provides easier access to data for business development purposes. Digital documentation of deviations allows the prompt documentation of what has been agreed during the project. It also allows openness and transparency in projects, which are essential buildings blocks of good quality control. At the moment, not all meaningful deviations are recorded; thus, the project parties cannot return to them later on.

Interviewed companies emphasized that inter-organizational digital deviation management should benefit all the various project parties involved in design, production and installation. The reason for recording deviations must be that everyone can improve their performance, not that they get more money from their work. Not every nipple information should be recorded and passed to all project parties. Thus, data on deviations should go through some sort of filtering before sharing to other project parties.

In the end, the purpose of digital deviation management should be learning. Companies would like to learn where problems, in general, occur in planning, manufacturing, and assembly, and what could be done to prevent these problems in the future. Different parties are interested in a bit different project issues; for example, designers would like to learn what the effect of design errors are on the additional site work. The designers also envisioned that if there was an information system to report all deviations and every project party could use it, the site could record all deviations in the foundation. The system could run an analysis on all the designs of schools and see where the biggest problems in the designs exist. At the moment, it is not known how good the designs of schools really are from the site's perspective.

The researchers envisioned a process for inter-organizational issues management system. Figure 6 illustrates a process for reporting inter-organizational deviations in a cloud-based management system.

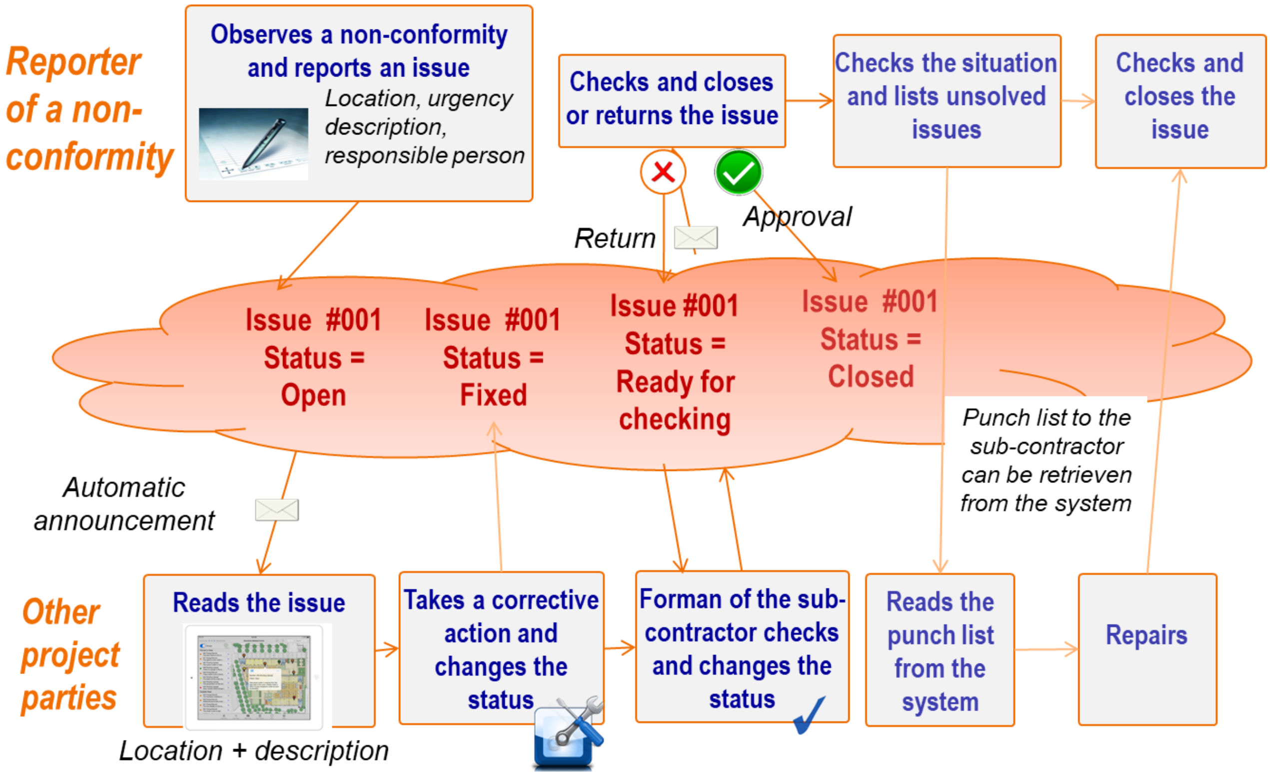

Figure 6. A process for reporting inter-organizational deviations in a cloud-based management system.

4.4 Requirements for an inter-organizational digital deviation management system and process

All interviewees agreed that deviation management necessitates easy tracking and recording of the quality deviation and its status until its resolution. Thus, deviations should be classified and formalized to enable its registration and resolution using digital means. Workers should be able to access the system from their mobile device. The system should locate the worker and allow an easy and visual mapping of the deviation to the model object.

The companies considered essential that deviation reporting should be as simple as possible so that it does not take too much time or effort. The reporter should at least record what has been observed and at what stage the deviation is detected so that analysis could be conducted later on. From the quality manager's point of view, probably three categories are needed: Deviation has been reported to the system, corrective actions identified, corrective actions implemented.

Three workshops were organized to define the requirements of the inter-organizational quality management system. The main effort was put on defining the data and variables which should be registered and shared digitally in order to improve quality in construction systematically. The proposed quality management system and its levels are presented in Figure 7. In this system, we use term *non-conformity* when speaking about deviations, as non-conformity better describes failure to meet specifications or requirements set for the work or product. At a non-conformity level, observed individual non-conformities are managed and corrected in the project. At a project level, project team and supply chain aim at monitor quality in the project and make corrective actions to prevent similar non-conformities in the same project. At a project portfolio and supply-chain level, actors in the construction ecosystem aim to learn from earlier quality observations, non-conformities and their correction processes.

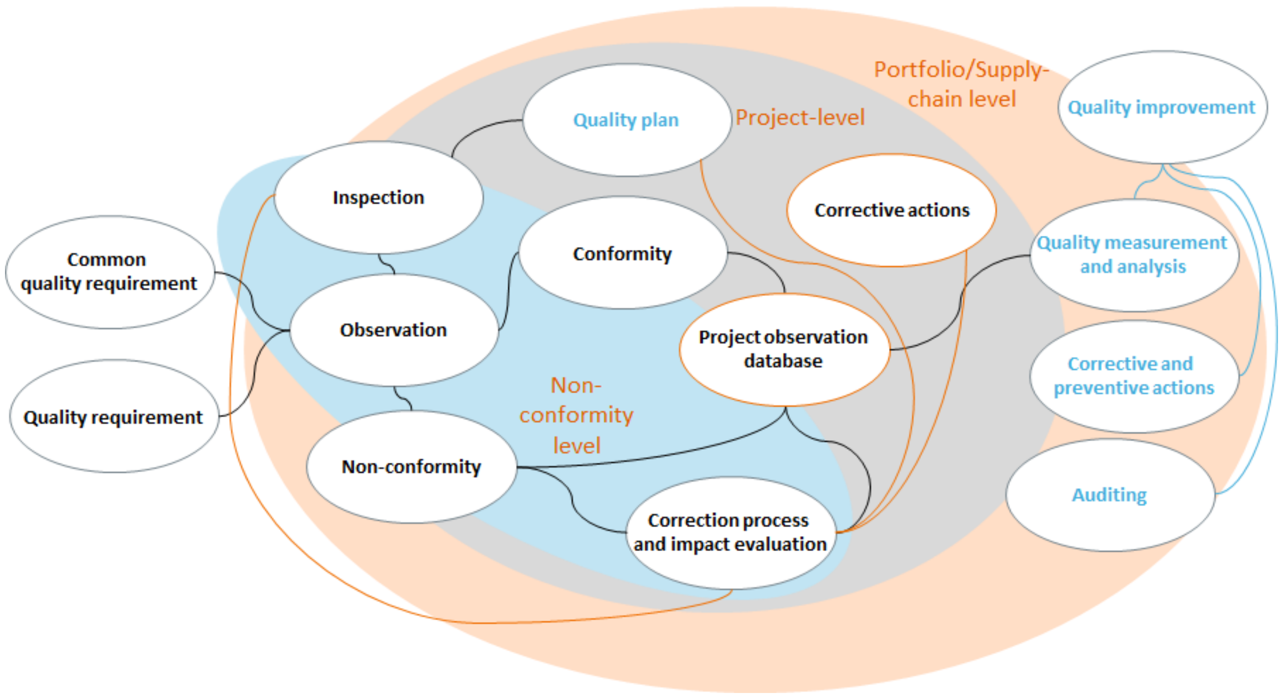

Figure 7. Quality management system at non-conformity, project and portfolio/supply-chain levels.

The developed system should produce digital and structured data for each of those levels. It was also discussed that data content should be filtered and anonymized when moving from a non-conformity level to higher levels. For example, two competing companies may be working on the same project. If the project is not a collaborative alliance project, it would be reasonable that non-conformities of one company are not shared with its competitors. Similarly, at a portfolio and supply-chain level, data should be anonymized so that project or actors cannot be identified from the data. Regarding the supply chain, it was discussed that in addition to quality observations made on construction site, the quality management system should cover quality issues in prefabrication and pre-assembly of project-specific elements and modules, such as concrete elements and bathroom modules.

In the next phase, the data requirements for quality observations and non-conformities were defined. First, the data was divided into four categories, 1) inspection, 2) observation, 3) non-conformity and 4) correction process and impact evaluation, reflecting the typical sequential process of quality management projects.

The attributes and data options regarding inspections phase are presented in Table 2. The inspection procedure is typically connected to the project's quality plan, which defines in which tasks the different inspections will be made. Required quality inspections agreed at the industry level set basis for the inspection types. Inspection types and methods vary from element production and acceptance inspections to guarantee inspections made after the project completion. The object of inspection is another important attribute to register and share. Here, several options could be registered. Production work using, e.g., Talo2000 classification system, is important information to differentiate quality issues of different works and assembly activities. Location information is important, especially for non-conformity and project level quality management. In frame construction, the inspection could be connected to planned blocks and floors. In interior construction, apartment codes and rooms provide more specific location information. Virtual spaces with a connection to designs can also be used, e.g., when locating quality observations of roofs. In many situations, connecting inspection to a specific building element, structural part of even commercial product may be the most relevant and meaningful way to locate inspection and related observation. Other relevant attributes related to inspections include the responsible actor or organization of the object of inspection, inspector and other participants, related contract and a contract method. Registering the contract method (e.g., fixed, unit or target price) may provide relevant information when selecting the appropriate method for similar works in further projects.

Table 2. Requirements for data collection of quality inspection.

Inspection	
Attribute	**Options**
Inspection type / method	ONE OF THE FOLLOWING: Factory production inspections; Material/component acceptance inspection; Model work; As-built dimensions; Tests and measurements; Partial work acceptance inspection; Work acceptance inspection; Self-inspection; Examination procedure for approval; Guarantee inspection
Object of inspection	SEVERAL OPTIONS: Production work; Location (block; floor; apartment; room; virtual space) Building element; Structural part; Product - Both classification variable and instance information needed
Responsibility and participants	SEVERAL OPTIONS: Responsible actor; Inspector; Other participants; Contract code; Contract method - Both classification variable and instance information needed
Time	Date and time

After inspection data, the next relevant element of the data model is a single observation. It should be understood that process can also start from the observation without any connection to the planned inspections. Therefore, the object of inspection and information about observer should be able to register in this phase. Otherwise, important attributes include the fulfilment of a requirement, which means mostly conformity or non-conformity of the observation related to the quality requirements. If some measurement is done the value of that should also be connected to the observation. Reference documents can also be attached, including general quality requirements and images of both positive and negative observations. Images are important at issue and project levels, but they would also enable later quality detection algorithm developments using, e.g., machine vision technologies. Therefore, it is important that images also from conformity cases are registered into the quality system. (Table 3)

Table 3. Requirements for data collection of quality observation.

Observation	
Attribute	**Options**
Fulfillment of a requirement	Conformity; Non-conformity; Other observation
Measurement	Result of measurement and measurement unit
Object of inspection (see Inspection)	Used if observation is not connected to any inspection
Reference documents	Quality requirements; Image of both conformity and non-conformity observations; Other documents

If the observation is correct, the process can be closed. Instead, if non-conformity related to quality requirements is observed, data regarding this non-conformity should be deepened (Table 4). For management purpose, it would be first critical to add an identifier to each observed non-conformity. After that, the type of conformity should be defined using standard options. It is important to notice that defining the type might require some extra information, e.g., on the available material or possibilities to correct the product. In the next phase, the immediate cause of non-conformity is defined. We used here Sacks et al. (2003)[7] classifications of design errors and added options regarding site-specific causes. It should be possible also to add multiple causes if needed. The idea of root cause information is to provide deeper knowledge on circumstances, and background factors that contributed to the emerge of non-conformity. Here we used Love et al.'s (2013)[8] typology of errors in construction. As root causes are always case-specific and generic typologies would never be accurate enough to provide needed understanding for learning, free text to describe the root cause is suggested to be added in the data model.

[7] Sacks et al. 2003. Process improvements in precast concrete construction using top-down parametric 3-D computer modeling. PCI Journal, 48(3).

[8] Love et al. 2013. Reviewing the past to learn in the future: Making sense of design errors and failures in construction. Structure and Infrastructure Engineering, 9(7).

Table 4. Requirements for data collection of the observed non-conformity.

Non-conformity	
Attribute	**Options**
Identifier	Identifier to specify non-conformity in the project
Type of non-conformity	ONE OF THE FOLLOWING: Unplanned assembly/work; Undone (product/material available); Undone (product/material missing); Imperfect assembly or work; Defective product (should be changed); Defective product (could be repaired)
Cause of non-conformity	ONE/SEVERAL: Damaged; Flawed assembly or work; Flawed delivery; Manufacturing defect; Error in detailed design; Design coordination error; Error due to poor management of design change; Error in original design; Other cause
Root cause	ONE/SEVERAL: Organizing; Expertise; Communication; Product defect; Lapse; Other root cause
Description of root cause	Free text to describe the root cause and the cause-effect chain to the non-conformity
Type of planned correction	ONE/SEVERAL: Dismantling; New product; Rework/reassembly; Repair on site: fitting and adjustments, clean, repair; Other correction
Responsibility of correction	Repairer
Seriousness	Critical; Non-critical
Due date of correction	Date

Type of planned correction should be typically decided in collaboration between the inspector and responsible actor or worker. The correction can include multiple activities. Dismantling is relevant in, e.g., situations in which some work has already been done without needed prerequisites. In that phase, also responsible repairer is defined. Seriousness reveals if the non-conformity affects the work on the critical path of the project. Critical non-conformities should be corrected immediately, whereas more time can be given for non-critical issues.

In the fourth phase, information about the correction process and the impacts of non-conformity are added into the database (Table 5). Payer and status of the correction are relevant mostly for the non-conformity and project level management. Cost impacts of correction, instead, are important also when actors want to learn from the most critical quality issues. Indirect costs may include, e.g., costs due to delays in other works and the whole project. It is also useful to describe effects which cannot be monetized, such as safety-related negative effects. Free text about key learnings and takeaways would smoothen the learning process in further projects and make implicit knowledge created around the issue more explicit and transparent.

Table 5. Requirements for data collection of the correction process and impacts of non-conformity.

Correction process and impact evaluation	
Attribute	**Options**
Financial responsibility of correction	Payer of correction
Status of correction	ONE: Repairer informed; Started; Done; Approved
Type of made correction	ONE/SEVERAL: Dismantling; New product; Rework/reassembly; Repair on site: fitting and adjustments, clean, repair; Other correction
Cost impacts of non-conformity	Direct correction costs (€); Indirect additional costs (€)
Other disturbance effect	Free text to describe negative effects of non-conformance
Learning from non-conformance and its correction	Free text to describe key learnings and takeaways from the non-conformance
Reclamation	Yes; No; Identifier
Reference documents	Bills; Receipts; Images; Other documents

In summary, the developed digital data model would enable the development of processes and systems which help managing quality issues in projects as well as enable effective learning from earlier issues and their management. However, more research and development work are needed for the practical implementation of the model and connection of the data content and structure with the existing data ontologies. Future investigation is also required to classify data and attributes defining on which levels they are needed and how to manage the rights to use them among the construction supply-chain actors.

4.5 Practical trial for sharing inter-organizational digital deviation data

The objective for this part of the research was to study the applicability of BIM Collaboration Format (BCF) API 2.1 standard for sharing quality deviation data between construction information management systems. In the study was created a practical trial software for testing BCF API features in few use cases with selected systems which were Trimble Connect and Congrid quality control software.

More general target was to recognize benefits and problems in the operative quality control process where the recorded observation data was processed in parallel systems by different stakeholders. As the trial concentrated in the technical application of BCF API, and there was no testing in real case environment, the findings are presented as a discussion of possible impacts.

Beyond operative quality control, the quality management includes analysis of the deviation data and implementation of needed corrective and preventive actions. In this research, one target has been inter-organizational sharing of quality data that would enable learning from other stakeholders and over individual projects. In general, the construction project's stakeholders may not be motivated to share detailed quality deviation data widely as it is an indication of stakeholder's capabilities and performance. However, adequately generalized and pseudonymized quality data may be possible to share more openly for predefined uses. This generalization process would require some semantic classification of the deviations like defining meaningful type, cause or impact for the deviation. During the trial, the major data types of BCF API were evaluated on how those could be populated with harmonized quality terms.

Trial implementation

BIM Collaboration Format BCF

BFC is intended for communication between construction project participants with a structured dataset that is transferred between information systems, and the data include a reference to BIM. BFC is a generic format, and message can contain information on any types of issues or notifications etc.

BCF is a buildingSMART International open BIM standard with two main methods: a file-based BCF data transfer and BCF REST API based service. In file-based exchange (XML formatted data) a BCF file (.bcfzip) is transferred from user to user in point-to-point manner. The web service based (RESTful) API mode for BCF involves the implementation of a BCF server for collecting BCF data and managing responses for the issues. As BCF refer to BIM, it is useful that BCF server can visualize the BCF data in 3D, so the BCF server functionality is natural addition to a collaborative BIM server which may have also UI for managing the BCD data. On the other hand, the BFC data can be accessed also from external software with BCF REST API.

BCF REST API 2.1

In the trial software, the BCF REST API was utilized. The details of BCF REST API are presented in public BCF-API repository[9]. Figure 8 presents the main data collections exchanged with BCF-API. The Topic contains label and descriptions of the topic with some classifying metadata for the topic. Some of the detailed properties are presented later. The Viewpoint contains the reference to BIM, either with a viewpoint in model geometry and/or referenced BIM object IDs. The Comment contains some partner's response to Topic. The topic may refer to external data like documents or URLs. All topics related incidences are recorded as Events. In addition to these core data types, the BCF-API contain methods for authorization of API usage and method to set project-specific enumerated lists for certain properties (see below).

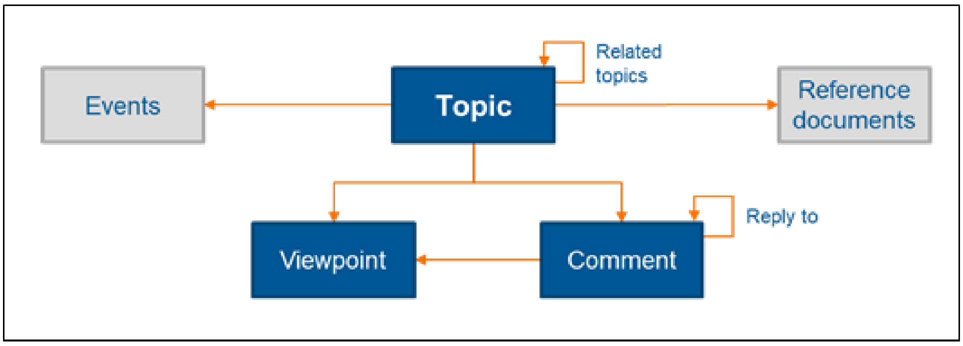

Figure 8. Main datasets of BCF-API specification.

Trial environment

[9] buildingSMART, BCF REST API Version 2.1, https://github.com/buildingSMART/BCF-API (Visited 29.10.2020)

The quality deviation data was transferred in BCF format between a software intended for site inspections and developed by Congrid Oy[10] and Trimble Connect[11], a collaborative BIM server. Trimble Connect has in current commercial version a legacy system to define and manage issues as so-called ToDos. In the trial was tested an alpha-version of BCF-API[12] implementation that in current setup converted BFC input as ToDos to show those in Trimble Connect user interface. Practically the Trimble Connect operated in this setup as a BCF-server.

The cloud-based Congrid software does not have BCF functionalities, but it has open API[13] that was used in the trial to convert the recorded quality issues into BCF format and upload those in Trimble Connect. The quality deviations are defined as Note/Issue in Congrid and notified and shared to responsible project partners like subcontractors. The Note/Issues are input with a mobile device at the site and have the possibility to attach photos and record the location in 2D-plan.

The Congrid system includes functionality for follow-up of the correction of a deviation. In the current practice, all construction project's main partners have user accounts in the system for commenting and notifying the progress of needed actions. The Congrid system contains also features for planning and managing inspections, provide inspection check-lists and project-specific settings like defining 2D floor plans etc.

Mapping data types

Applying BCF for transferring findings of quality issues required mapping between Congrid's data types to BCF. The Congrid have system-specific and more granular data types for inspection findings that are available in BCF format which required to define some rules for converting the data into BFC, for example, include several attributes into one BCF attribute. In the opposite data transfer, when BCF data is converted into Congrid format, it may be not possible to align the data to the correct attributes. This kind of approach concludes in a specific ad-hoc interface that requires maintenance if the Congrid source data change. The implemented mappings are presented below in "Tested use cases".

The integral part of BCF is the reference to BIM as a Viewpoint dataset. In the current version, Congrid does not provide BIM-related references. It is possible in Congid to attach the GUID of space in the space-hierarchy that is predefined in configuring the system for a project. In current practice, the user is expected to select the room space from dropdown-list to indicate the generic location of the issue. More detailed location is pointed in 2D drawing view of the user interface. If the GUID of IfcSpaces is included in space-hierarchy, those can be incorporated in BCF Viewpoint and shown in BFC-compatible BIM-software like Trimble Connect. However, the primary definition in Viewpoint dataset is the Camera settings which set a point and direction in the global coordinate system of viewing the model. With this setting, the model will be shown on specified view to the receiver of the BCF dataset.

Trial software implementation

A desktop application was implemented to test sharing inter-organizational quality deviation data. The application utilizes the public API (REST style API with JSON as the data format) of Congrid to communicate with Congrid. The Trimble Connect BCF REST API (Alpha version) is used to communicate with Trimble Connect (TC). In addition, Trimble Connect .NET SDK was used for managing the authorization with TC. The application is developed in Visual Studio 2017 in C# targeting framework .NET Framework 4.5.1 (and 4.5). A

[10] Congrid Oy, https://congrid.com/
[11] Trimble Connect, https://connect.trimble.com/
[12] Trimble Connect BCF REST API (Alpha), https://connectbcfapi.cloud.tekla.com/swagger/
[13] Congrid Public API, https://docs-v2.congrid.com/

more detailed report of software design and a user guide for the application is available for further developments.

<u>Tested use cases</u>

Trial testing included the following parts in transferring a Congrid quality deviation data with BCF-API into Trimble Connect.

In Table 6 are presented the BCF-API parameters that were used in a trial for defining a BCF topic. The correspondence of the parameters were selected by the development team. Most of the correspondences are obvious, but few data types in Congrid were combined in the “Description” parameter in BCF format.

BCF-API specification contains an “Extensions” method to define the project-specific enumerated selection list to input values for selected parameters. In the trial was used Trimble Connect’s hardcoded values for value lists as the alpha version of BCF-API did not support project-specific Extensions-definitions. The BCF Extensions functionality would make it easier to define the mapping as the value-lists could be defined according to the need of an external system like Congrid. However, in practice, there is a restriction as the BCF method is intended for any kind of issues in a project. This will probably conclude in generic definitions as those have to be used in any kind of topics. It would be possible to create more sophisticated BCF implementations if some of the parameter value-lists could be dependent, for example of the topic type.

It shall be noted that in Trimble Connect BCF-API, the user data for “creation_author” and “modified_author” are set according to the user account that is used for BCF-API interactions. Also, the corresponding date/time data is set to the time of uploading data. This means that the original creation and modification metadata is over-written for these data types. This emphasizes that the BCF-API of Trimble Connect is operating as BCF server that is expected to be used with client software online and not as data shared in parallel systems. The use cases in the trial were initially intended for the latter option like synchronizing quality inspection data in Congrid with Trimble Connect.

Table 6. Mapping of BCF-API data types with Congrid Note parameters.

BCF-API Topic parameter	BCF-API Description	Congrid parameter	Example data
topic_type	The type of a topic[1]	noteTypeId	"QUALITY_INSPECTION"
topic_status	The status of a topic[1]	statusId	"INCOMPLETE"
title	The title of a topic	description	"Liimatahroja"
priority	The priority of a topic[1]	priorityValue	0
labels	The collection of labels of a topic[1]	categoryTagRelations	[]
assigned_to	UserID assigned to a topic[1]	companyId	"gvDlAklhdI5KbOs25wKp1tXUKwzxOroZ" (Yritys Oy)
stage	Stage this topic is part of[1]		
description	Description of a topic	descriptionExtended	"Puhdistettava matolle sallitulla liuottimella"
		targetId	"Pd5TOfLEUJHFjzKfyLfZOBOtEVHWhdTH" (Huone 123)
		workSectionId	"488838" (Mattotyöt)
		requiredAction	"Liima poistettava"
due_date	Until when the topics issue needs to be resolved	requiredActionDueAt	"2020-09-16T09:00:00Z"
creation_author	userId of the creation author[1]	createdBy	"20835" (etunimi.sukunimi@yritys.fi)
modified_author	userId of the modified author[1]	modifiedBy	"20835" (etunimi.sukunimi@yritys.fi)
creation_date	creation date of a topic	createdAt	"2020-09-10T10:26:11.854000Z"
modified_date	modification date of a topic	modifiedAt	"2020-09-10T10:29:03.072568Z"

[1] *The values of marked parameters are enumerated lists that are defined in a project-specific settings file "extensions.xsd".*

One part of mapping data types in the trial was to define equivalent options of the values in a few enumerated lists. In Table 7 is shown the defined mappings. The enumerated value-lists differ, for example, in the number of items but mostly equivalent items were identified. Possible methods were discussed to cover missing items like in the status values. In any case, this mapping and managing missing value-items lead in the complex and non-standard interface. Table 7 shows also that all Congrid quality deviation Notes were set in BCF conversion in a topic type of "Issue" and no other types available in Trimble Connect was used. In general, there is an obvious need for a harmonized set of needed quality deviation classification items which would enable better data analysis and follow-up of the achieved quality level. Those are discussed in 4.3 and 4.6.

Table 7. Mapping of predefined value-lists. The Trimble Connect value options were hardcoded in the Alpha version. Also, Congrid values are system-specific.

Trimble Connect		**Congrid**	
Topic parameter	Parameter values	Note parameter	Parameter values
Priority		priorityValue	
	Low		
	Normal		0
	High		
	Critcal		1
Status		StatusID	
	New		Pending
	Waiting		Received
	In progress		Incomplete
			Rejected
	Done		Completed
			Verified
	Closed		Accepted
Type		noteTypeId	
	Undefined		
	Comment		
	Issue		"QUALITY_INSPECTION"
	Request		
	Fault		
	Inquiry		
	Solution		
	Remark		
	Clash		

<u>Conclusions</u>

The implemented trial for sharing inter-organizational digital deviation data indicated that BCF REST-API method is intended for a centralized BCF-server that may be used with online client software or the BCF-server have specific user interface for managing BCF data. The method is not actually suitable for shared data management in parallel systems.

BCF format in general is very flexible and can be used for managing any kind of issues in a construction project and there is methods to configure BCF for the specific needs of a project. The configuration is done with enumerated lists of strings which will require human interpretation of data or the partners shall agree of the meaning of the data strings. This approach supports projects specific usage of the BCF method but limits further usage for quality data collection and analysis for improving quality in wider scale.

4.6 Ontology for quality deviation management

Quality deviations in construction projects often touch many different organizations, from on-site workers to designers, fabricators, product vendors and logistic companies. In such a decentralized environment, a shared terminology and interlinked representation of quality deviation information, understood by different parties in a similar manner, could support their accurate detection, identification of their causes and origins, and efficient interorganizational processes for managing quality issues.

In the Diction project a comprehensive ontology – Digital Construction Ontology (DICO) – has been developed to capture the state of the construction project to offer a shared situation picture to project participants, in order to enhance the coordination of activities among them. In this subsection we study, what would be the representational mechanism in DICO to enable the organization, linking and sharing of data about quality deviations, and whether there are specific areas where the DICO ontology should be refined or extended.

As a result of the research carried out in the Diction project, the following representational areas concerning quality deviations have been identified:

1. *Quality issue management*:
   a. *Quality issues*: The representation of quality deviation issues, including
      - linking with the relevant building objects, locations, and agents,
      - the urgency, importance and state (open/closed) of the issue,
      - metadata, such as creator and time of creation of the issue, and
      - classification of quality issues.

   b. *Quality issue processes*: The representations to support the assignment of responsibilities and handlers of issues, the definition of processing steps to resolve an issue, and the relationships between issues such as derived issues and parent issues.
2. *Quality deviation detection*:
   a. *Acceptability*: Since quality issues mean a variation from a requirement or expectation regarding a characteristic of an object, some quality issues can be generated automatically from the inspection or measurement results. In simple cases the requirements can be represented as an acceptable range of values for a property of an object. In more complex cases it could be based on recognition of acceptable observations, where the model is generated with reinforcement learning methods.

   b. *Quality deviation detection processes*: The representation of processes needed for quality deviation detection. For example, the process may involve shooting a video to capture the state of construction, extracting segment belonging to particular locations, extracting images, matching and aligning images with BIM models, detection of deviations, and so on.
3. *Root cause analysis*: A properly maintained, interlinked model of a construction project would enable the identification of activities and agents relevant for specific quality issues. Therefore, it would support the tracing of the origin of a quality deviation. The support for root cause analysis is thus an inherent property of construction project model based on linked data.

In Digital Construction ontologies suite (DICO) – documented and published in different machine-understandable formats at ***https://w3id.org/digitalconstruction*** – the concepts of quality issues management naturally integrate with the existing representations of information entities and issue management. An example is shown in Figure 9.[14]

[14] The term bfo refers to Basic Formal Ontology (ISO/IEC 21838-2) and other prefixes to different ontologies as follows:

- dice: https://w3id.org/digitalconstruction/Entities#
- dici: https://w3id.org/digitalconstruction/Information#
- dicv: https://w3id.org/digitalconstruction/Variables#
- prov: http://www.w3.org/ns/prov#

DICO has a concept for a quality deviation issue (***dici:NonConformanceIssue***) which is a subtype of an information entity (***dice:InformationContentEntity***), and as such is about something else (through the relation ***dice:isAbout***). The entities that an issue can be about include, among others, building objects (***dice:BuildingObject***), locations (***dice:Location***), and activities (***dice:Activity***) or states (***dicp:StateConstraint***). If the quality issue is linked to an activity, it is likely to have indirect links also to the building objects, locations and agents related to the activity. An issue can be connected to an inspection or observation activity in which it was produced (through ***prov:wasGeneratedBy***).

The metadata can be associated with quality deviation issues through provenance vocabulary, the creator with relation ***prov:wasAttributedTo*** and the creation time with ***prov:generatedAtTime***.

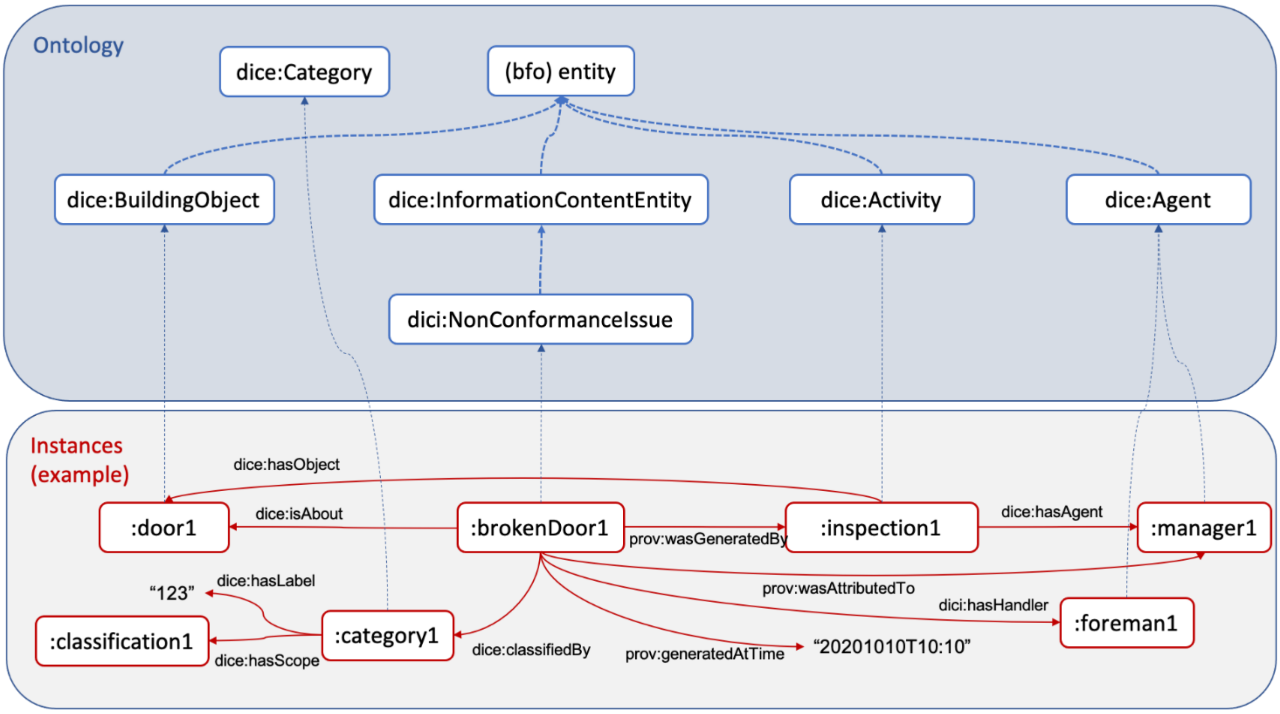

Figure 9. DICO classes for quality deviation issues with an example of instance data

Quality deviation issues can be associated with relevant classifications (though the relation ***dice:classifiedBy***) that are related to categories (***dice:Category***). Further effort is needed either to identify an existing classification of quality deviations or to develop a new classification for them. Some potential categories proposed in the Diction project are *missing* (not installed and unavailable), *uninstalled* (not installed but available), *inadequately installed* (e.g., loose), *defective* (can be fixed), and *broken* (must be replaced).

As part of issues management vocabulary, issues have a scope (***dici:hasScope***), they can be assigned handlers (***dici:hasHandler***), they can have parent issues (***dici:hasParentIssue***), and they can be associated with a solution (***dici:hasSolution***), a plan to correct the quality deviation.

As of now, the technologies for automatic quality deviation detection are still under active development. For instance, the applicability of advanced techniques from artificial intelligence research is being explored, including machine learning and integration of computer vision with ontologies. Consequently, the requirements for the ontology are still evolving. The ontology work in this area needs to study specific use cases in detail.

However, some aspects of quality deviation detection can already be represented with the existing mechanism of DICO. The simple requirements for acceptable property values can be represented with different types of DICO constraints (***dicv:Constraint***). Moreover, the processes and the derived information entities seem to fit the exiting classes of DICO. Furthermore, the relevant relations can be represented with the terms from the PROV-O provenance ontology[15].

Figure 10 shows an example of the entities involved in the quality deviation detection process based on computer vision. In the middle of the figure (red area) contains a fragment of the drywall building process. The states between activities are also indicated since the purpose of computer vision is to detect the states of the process. In addition, the detection tries to identify possible deviations from the requirements, especially those concerning geometry (for instance, an electric socket at wrong location) and surface quality. The process utilizes the BIM model of the building as a source of geometric requirements. The entities related to computer vision are in the lower blue part of Figure 10. The detection process starts from the bottom when a video is shot of the building by walking through it. The video is segmented based on locations, and each segment is linked to the particular location (the blue link, ***dice:isAbout***). The video segment is aligned with a BIM model, and images of different building objects (in this case, a drywall) are extracted from it. The image is matched using a machine learning model with the state, based on its features extracted from the BIM model. The geometric deviations can then be recorded as quality issues (***dici:NonConformanceIssue***).

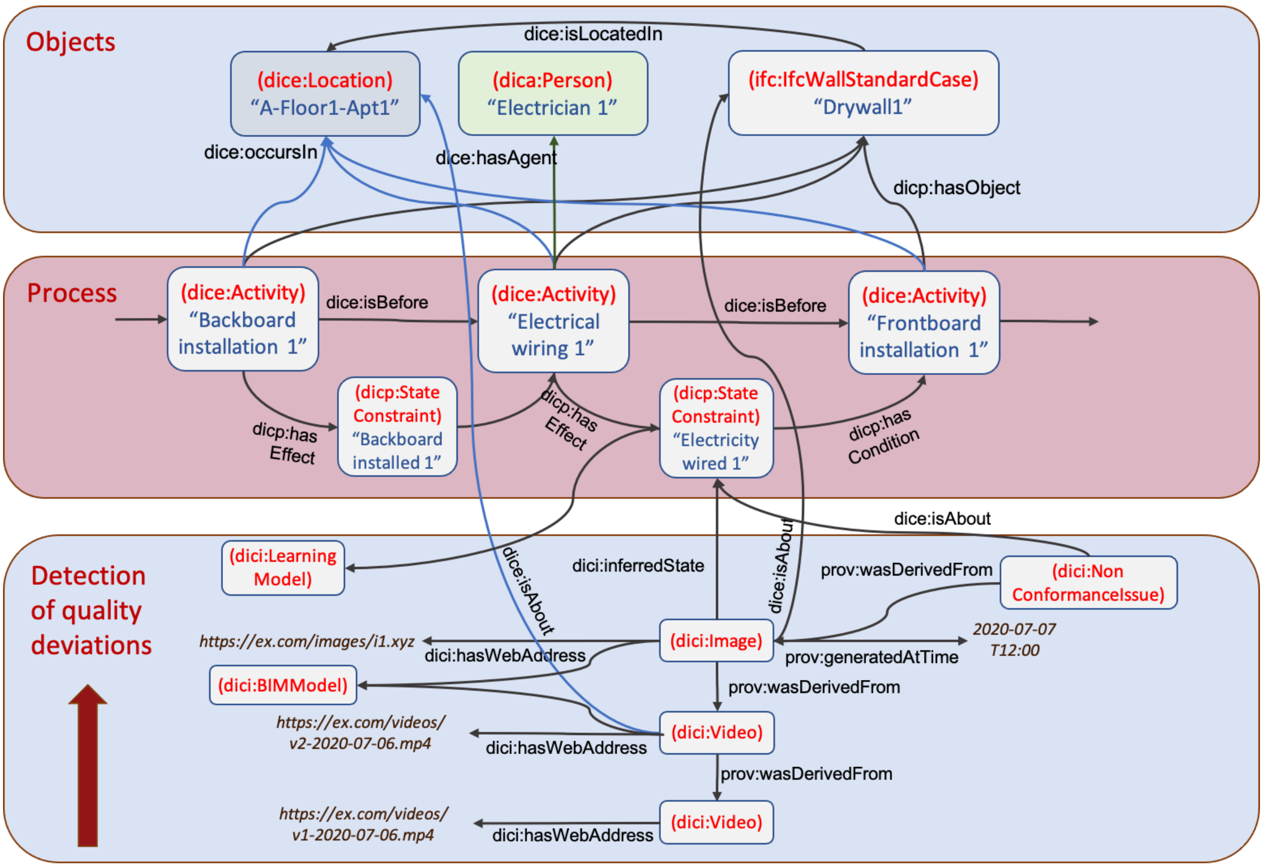

Figure 10. Detecting quality deviations using computer vision

The support for root cause analyses is facilitated by the ontology-based representation of interorganizational processes and interlinked models, whereby it is possible to identify which activities have been performed on defective parts, who are the vendors of associated products or materials, which agents worked on the

[15] PROV-O: https://www.w3.org/TR/prov-o/

activities, whether the execution of activities faced some adversities (such as broken equipment, missing labor, overly tight schedules), and so on. It should be noted that the root cause analyses, especially if they concern a collection of similar deviations, could benefit from such interlinked data gathered in the longer term from different projects. The ontology-based linked data representation can be a crucial enabler of those analyses.

The work needed to develop DICO ontology to support quality deviation management properly can be summarized as follows. Firstly, the issue management aspects of quality deviations can already be represented using DICO ontologies, naturally with the support of other relevant ontologies such as IFC ontology for BIM models and the PROV-O ontology to model the origin of the information. This part of the ontology needs to be tested and possibly refined with real data. Secondly, further refinement and development work would be required to capture the concepts needed to support the automatic detection of quality deviations. Since automatic detection techniques themselves are still in development, this area will probably remain under work in the foreseeable future. Finally, root cause analysis can be supported by models based on linked data; these possibilities should be explored in more detail by developing specific root cause analysis tools utilizing linked data.

It should be noted that the benefits of ontologies will only be gained after the relevant data can be accessed in terms of ontologies and after the entities are properly linked with each other. These tasks are not necessarily complex but would still require that sufficient effort is allocated to software development.

4.7 Conclusions

The key to successful deviation management is early planning and parties' commitment to ensuring quality in projects. Quality in projects is the responsibility of each project party. The project parties should organize a kick-off meeting at the beginning of the project to identify the critical spots in the project to prevent unnecessary deviations. However, as projects rarely go as planned, another success factor of deviation management is an easy-to-use information system for tracking and analyzing deviations.

At the moment, deviation management in construction is part of each project parties' quality management processes which are quite systematic and follow quality management standards. Information on deviations in projects are mainly handled between two or three companies, often in the form of phone calls or email. The party making the corrective actions reports the deviation into their company internal Excel or information system. The digital data on this deviation is not shared with other project parties, and the data is not used for inter-organizational learning purposes. Thus, the same problems tend to occur again and again, even in similar types of projects. The key question to answer is how to manage data on deviations in construction projects so that learning is enabled and typical problems are avoided in future projects.

Inter-organizational digital deviation management could be a solution to enable transparency and project-to-project learning. Project deviation management necessitates the tracking and recording of the deviation and its status until its resolution in a standard machine-to-machine readable format. Thus, deviations should be classified and formalized to enable its registration and resolution using digital means. In the best case, the deviations could be mapped into the objects of design models, since these objects have unique identification numbers.

Further research work needs to be conducted to determine incentives for sharing deviation data. Which incentives would encourage construction parties to share deviations at the beginning of this development when no analysis can yet be delivered to the companies? Once there is enough data, analysis can help in the learning process of companies, and encourage companies to share data. One option to incentivize is also that the requirement to collect deviation data is written into the contracts, and thus it is required by the owner of the project.

At least, the deviation data should be anonymized in order not to single out companies or specific projects, and thus increase parties' willingness to report issues. Also, the system should be as simple and automatic as possible. The worker should be able to take a snapshot, and the system should automatically link it to the model object, location and the work currently ongoing. This concept would resemble the commercial tool BIMcollab[16] , which is a cloud-based issue management system.

Further research endeavours should also focus on identifying who is the party capable and incentivized enough to take ownership of the inter-organizational deviation management system. One possible party could be the Construction Quality Association (RALA[17]) that aims to improve the standard of quality in the construction sector in Finland. Another possible party could be the Confederation of Finnish Construction Industries RT[18] since the organization launched in 2019 a project for improving the reputation of the construction sector (mainetalkoot, in Finnish).

5 Company results: Ruukki Construction (Building Envelopes)

The main goal of Ruukki's Construction Building Envelope unit in the Diction project was to add intelligent features to building components and to open up digital services for Ruukki's customers to track orders and deliveries.

The project developed condition monitoring services integrated into the building's shell structures. A measuring system was developed for monitoring the snow load of roof structures based on load-bearing steel sheet profiles, which operates both completely locally and can also be connected to building automation systems or remote monitoring. In addition, humidity monitoring based on radio impulses in wall structures was piloted.

The project developed and opened a portal for Ruukki's customers, which provides direct access to up-to-date information on Ruukki's ERP system about the customer's own orders, the production phase and deliveries. The information can be grouped and filtered in several different ways according to the need for use, e.g., by delivery, package or product. The system will also be connected to the delivery location and tracking service ETA (Estimated Time of Arrival) with its services. Development work has also begun to integrate data models into sandwich panel deliveries. This will make it possible, for example, to identify packages or individual panels and visualize their location in a 3D model of a building controlled by a mobile device. The system also allows installation status information to be added to the customer portal.

[16] https://www.bimcollab.com/en/default
[17] https://www.rala.fi/english/
[18] https://www.rakennusteollisuus.fi/English/Frontpage/