Digitalizing Construction Work-flows (DiCtion)

Final report

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1. Introduction

1.1. Background of the research and development project

Construction industry is suffering from low productivity, high risk of delays and cost overruns. Globally, productivity growth in construction has averaged only 1 percent a year over the past two decades, compared with the growth of 2.8 percent for the total world economy and 3.6 percent in manufacturing. At least 20% of the total construction volume is waste, 30% of construction is rework, 40% of jobsite work is unproductive, 40% of projects are over budget, and 90% of projects are late (c.f. Forbes & Ahmed, 2011). Typically this is blamed on the seemingly complex and chaotic nature of construction production. Complexity arises from the fact that currently no one has an accurate picture of what has happened and what is happening now, and there is a very unclear picture of what is going to happen in the future. The vision of the DiCtion project was to solve these problems by digitalizing construction workflows; All construction project stakeholders should have a shared understanding of past, current and future situation picture.

The DiCtion project investigated various ways to achieve the shared situation picture. A key challenge that we explored was that different project stakeholders have their own view of the construction schedule because they are thinking in terms of their own work. In earlier attempts to resolve this, rigid approaches have been implemented, for example by forcing everyone to follow the same breakdown of work and locations. However, this rigid breakdown does not work well for any one of the parties and results in difficulties in updating information or adapting to changes. Our goal was to allow freedom of action for each stakeholder and to be able to combine the freely generated information into one, shared, project situation picture to enable collaborative planning. This required research and development related to developing underlying data models, creating the rules necessary for integrating information on a construction project level, enabling freedom and collaboration in planning future work, and finally finding out in real time what has happened before.

1.2. Participants

Participants of the project all had interest in situation picture and had done some related work in previous projects. Aalto University had developed location-based planning and controlling approaches, integrated them with collaborative planning, and real-time tracking of resources (iCONS project) and using images for reality capture (RECAP project). VTT had developed proof-of-concept implementations of Linked Building Data on Drumbeat-platform (Drumbeat project) and is currently utilizing technology in facility management of bridges (Smart Bridge

FM project) and for linking building IoT systems (VIRPA-C project). Trimble planned to develop practical tools for managing and sharing the situation picuture of the construction project.

End user companies involved in the project included Fira, a contractor planning to scale their business by better analysis and management of information and new technology. Sweco is a consultant company aiming to digitalize their operations. Ruukki aimed to increase productivity and decrease cycle times by more transparent operations, while Consolis Parma wanted more collaboration and transparency in the supply chain. Bonava wanted to explore intelligent construction products. The goal of all participating companies was to improve the domestic and international business by implementing or using shared situation picture.

1.3. Steering group

The steering group of the project included the following experts:

- **Jukka Suomi, Trimble Solutions Oy (chairman)**
- **Otto Alhava, Fira**
- **Mauri Laasonen, Sweco**
- **Timo Alanko, Ruukki**
- **Veijo Artoma, Parma Consolis**
- **Sampo Oksama, Bonava**
- **Seppo Törmä, VisuaLynk**
- **Markku Kiviniemi, VTT**
- **Olli Seppänen, Aalto**
- **Antti Peltokorpi, Aalto**

1.4. Project aim and methods

The project was divided to 8 work packages (Figure 1). In this report, we detail the key results of each work package. Additionally, each work package has a separate, detailed report. These reports can be found on the project website www.aalto.fi/en/diction.

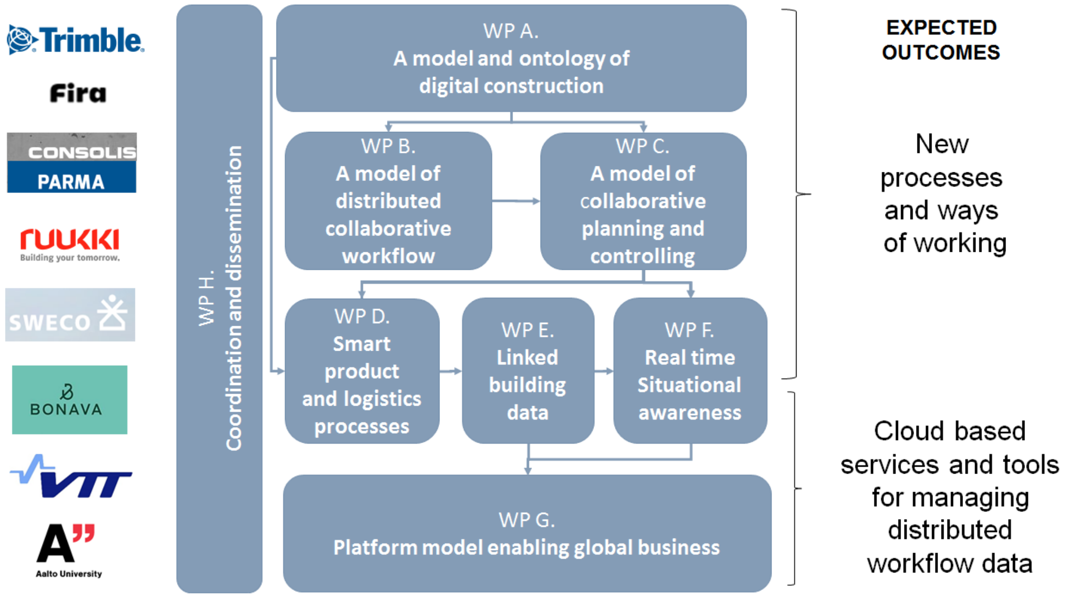

Figure 1: Work packages and participants

WP A: A model and ontology of digital construction

In this Work Package, the goal was to develop a conceptual model for situational awareness. The WP was implemented as a set of facilitated workshops and the key deliverable was a conceptual map of situational awareness.

WP B: A model of distributed collaborative workflow and WP C: A model of collaborative planning and controlling

The two work packages of the initial plan ended up being combined and the results are reported in one report. The goal was to develop a generic data model for creating, sharing and managing workflow data and to develop a model for collaborative planning and controlling using the digital situational awareness.

WP D: Smart product and logistics processes

In this work package the work focused on situational awareness in the supply chain.

WP E: Linked building data

The goal of the work package was to develop an ontology enabling situational awareness and making possible the linking of multiple data streams.

WP F: Real time situational awareness

In this work package we aimed to evaluate the different data streams of situation picture and reflect them back to individual plans and calculate KPIs based on situation picture.

WP G: Platform model enabling global business

In this work package, the goal was to evaluate possible business models related to linked data.

WP H Coordination and dissemination.

Several workshops were organized to get feedback on results. Workshops were organized in Finland, the Netherlands and Stanford University (CIFE) and two workshops were organized remotely during the COVID-19 pandemic.

2. Situation picture in construction

2.1. Background

An agent has *situation awareness* (SA) when it maintains an up-to-date understanding of the relevant aspects of its environment to enable fast, accurate and correct decision making. (The agent can be a person such as a worker, designer, manager or owner, or a team, corporation or even a software system). SA has been studied actively in military operations, aviation control, and naval control, mostly in single agent settings, and especially in mission critical, real-time decision-making situations.

Lundberg (2015) presents a holistic framework of situation awareness, distinguishing the following aspects:

- ***SA states***: What *objects* are there in the situation and what are their *states*? How are they interpreted against the *expectation frames* for the situation (e.g., plans, predictions)? What are the *implications* of the interpretation (e.g., unfulfilled precondition, failed activity, delay)? How will the implications *affect the near future*, within a relevant event horizon? What *corrective actions* could be used to solve envisioned problems?
- ***SA systems***: The *solutions to maintain and distribute* SA among participating agents and between system parts.
- ***SA processes***: Processes of *achieving and maintaining* SA, and relations to *processes of using* SA (for instance, in decision-making or coordination). How the SA is *updated* and what guides the updates?

Gathering of situation awareness needs to be directed by expectations of what should happen. There are frames or schemas that in an organized and pre-planned activity such as construction could be construction plans, and in an unplanned, improvised activity previously learned, known situation patterns that are evoked by some perceived cues. The active frames should affect the attention: what should be perceived in this kind of situation.

Achievement and maintenance of situation awareness has been divided into the following levels (Endsley, 1995; Nofi, 2000):

- ***Perception*** - Acquiring the available facts and observations through processes of monitoring, cue detection, and simple recognition.
- ***Comprehension*** - Understanding the facts in relation to the goals and plans, using pattern recognition, interpretation and evaluation.
- ***Projection*** - Envisioning how the situation is likely to develop in the near future provided it is not acted upon by any outside force.
- ***Prediction*** - Envisioning the near future, taking the external and random influence into account.

To underline, situation awareness does not result merely from collecting lots of facts and observations in an undiscriminating fashion. Instead, the collection process must be *guided* by the committed or expected courses of action (for instance, plans or simulations), and moreover, the collected facts and observations must be *actively interpreted* to put them in a relation with committed or expected courses of action.

Situation awareness has been studied a lot in single agent settings but there are also numerous settings where situation awareness must be maintained by several agents concurrently. When each agent has its own situation awareness, there is an overlapping, common part and non-overlapping, complementary parts of overall situational awareness. The common part is called *shared situation awareness* and the complementary part *distributed situation awareness*. Both shared and distributed SA can be important to coordinate potentially conflicting or complementary activities of multiple parties.

An interesting practical realization of situation awareness system in a military setting is the maintenance of a *common operational picture* (COP): "A single identical display of relevant information shared by more than one command. A common operational picture facilitates collaborative planning and assists all echelons to achieve situational awareness" (Gortney, 2010, p.42).

An important benefit of a shared SA or COP is that they enable individual agents to *make decisions relatively independently* from each other – that is, without checking each time from others if the decision would be fine for them – and *still avoid conflicts and achieve a level of coordination*. This would certainly be useful in construction sites where different people constantly need to make decisions, big and small. Obviously, the level of coordination achieved depends on the accuracy and quality of shared SA.

2.2. Workshops to define the concept

To study the nature of situation awareness in construction management, empirical data was collected through interviews in California and Finland, and by organizing four workshops with construction professionals from DiCtion project consortium. They resulted in a refined view on the situation awareness in construction, summarized in the following observations.

1. *Forming a SP* – It is challenging to form a situation picture of construction since the actual workflow deviates from the planned workflows. The reasons are that the plans may conflict with the natural or practical workflows adopted by the workers especially in the presence of obstacles, and also that is difficult for the workers to follow the plans due to insufficient tool support.
2. *Learning* – Workers have no channels to give feedback when plans are not feasible or practical. Since information only flows from top-down, the workers' knowledge of detail-level problems on-site does not lead into learning that would improve the plans in the future and make them more feasible and practical. Concepts of SA nor COP do not address learning in a proper manner.
3. *Requirements* – The requirement for the situation picture is that the scope, quality and accessibility of produced operational information is adequate for controlling the workflow and improving production processes.

4. *Process phases* – The process of data collection and analysis for understanding productivity consists of three phases: (1) data acquisition through change tracking, sensing or perceiving; (2) information storage, interpretation and refinement in human or computer memory systems; and (3) data distribution in the form of user interfaces and social interaction.
5. *Manual and automatic* – Data acquisition, interpretation and distribution are divided into manual and automated processes and they are interconnected, and it needs to be taken into account when designing information management systems that aim to improve the situation picture in construction.
6. *Benefits* – The situation picture would have also other benefits besides operational coordination and efficiency. It would have the potential to improve workers' safety, improve designs based on feedback from on-site operations, reduce disputes, improve logistical plans and uncover hidden work.

It should be stressed that the situation picture needs to be maintained in references to the planned workflow that needs to be practical and realistic enough that it can be followed. The development of more useful and pragmatic plans requires the capability to gather realistic information from actual workflows to work as a basis of learning.

2.3. Maintaining a shared situation picture

The primary goal of Diction was to develop an information management solution to maintain a *shared situation picture*, to support situation awareness in coordinating daily operations and supporting operational planning in construction projects. From that perspective, the shared situation picture is a technical solution that provides all project parties consistent real-time information about relevant status of project execution:

- What is the status of activities: completed, ongoing, interrupted, delayed?
- What is the status of entities such as models, documents, contracts, procurement packages, physical building elements, building systems, resources, or temporary constructs?

A situation picture should be shared and distributed in a sense that

- each party would see the parts of the situation that are relevant to its activities, and
- the views of all parties are consistent with each other to facilitate the synchronization and coordination of simultaneous activities of multiple parties.

The technical maintenance of a situation picture requires, first, the capability to gather detailed real-time data from different aspects of a construction process. As mentioned, this can be partly automatic and partly manual process. However, people are reluctant to do repetitive cognitive tasks – even simple ones such as writing progress updates – and the information they provide can also be inaccurate or biased. Since practical availability of sensors and imaging solutions is growing, the maintenance of situation pictures will gradually become more automatized. A prerequisite for that is the capability to integrate the data gathered from these automatic channels into a unified picture. This requires a principled conceptual model that connects construction activities to the entities from which sensor observations are made.

2.4. Conceptual model of situational awareness

In Diction the approach to integrate data to maintain the situation picture is based using or defining suitable ontologies that cover the concepts and relations in the construction domain. In Diction, the following requirements were identified for the coverage of the ontologies:

1. To represent the entities in the *domains* of construction management, building information models, and supply-chain management.
2. To support the advanced *construction management methods* such as Location-based Management Systems, the Last Planner, and Takt production.
3. To relate sensor systems and *sensor data to observed construction entities*, such as workers, locations, material batches, and equipment.
4. To relate *observed construction entities and their states to construction activities* in a way that the enablement, progress, and completion of activities can be inferred.

Sensor data can usually be gathered by observing the *various ingredients of activities*: building elements, agents, locations, equipment, and material batches. The primary interest from the perspective of situation picture is *the execution and progress of activities* that unfortunately is difficult to observe directly. However, it can be inferred from what happens to the ingredients. This suggests, therefore, that a sound and operationalizable approach is needed to link the activities to their ingredients.

Due to the above-listed requirements, the approach selected in Diction is based on *activity-flow modeling* (Garcia-Lopez, 2017) developed in the field of lean construction (Koskela, 1999, 2000). Consequently, the ontologies need to define the concepts and properties to represent the following ingredients of activities:

- *objects* that activities are focused on and whose states define the precedence constraints between activities (from BIM models and product data management),
- *workspaces*, that is, the location resources of activities (partly from BIM models),
- *agents* such as labor crews (from resource management),
- *materials* consumed by activities (partly from BIM models),
- *equipment* needed by activities (from resource management),
- *information entities* such as BIM models, drawings or instructions (from document management), and
- *external conditions* such as temperature and humidity (from sensors).

In addition to sources of data mentioned above, the locations of many resources can be tracked with sensor systems for positioning and identification, and the availability workspaces with occupancy sensors.

The central concepts of a situation picture are shown as blue boxes in Figure 2. The information sources at the outer circle are shown as grey boxes. The upper part of the figure (with reddish background) indicates the area of traditional construction management. The lower part (with bluish background) shows the new opportunities, including object tracking, sensor systems, BIM, product data repositories, and so on. The overall goal is indicated by the brown arrows in the middle of the figure: to make the information flow from the different ingredients to the activity, in order to produce the understanding the progress of activities. These arrows need to be defined as proper relationships in the ontologies.

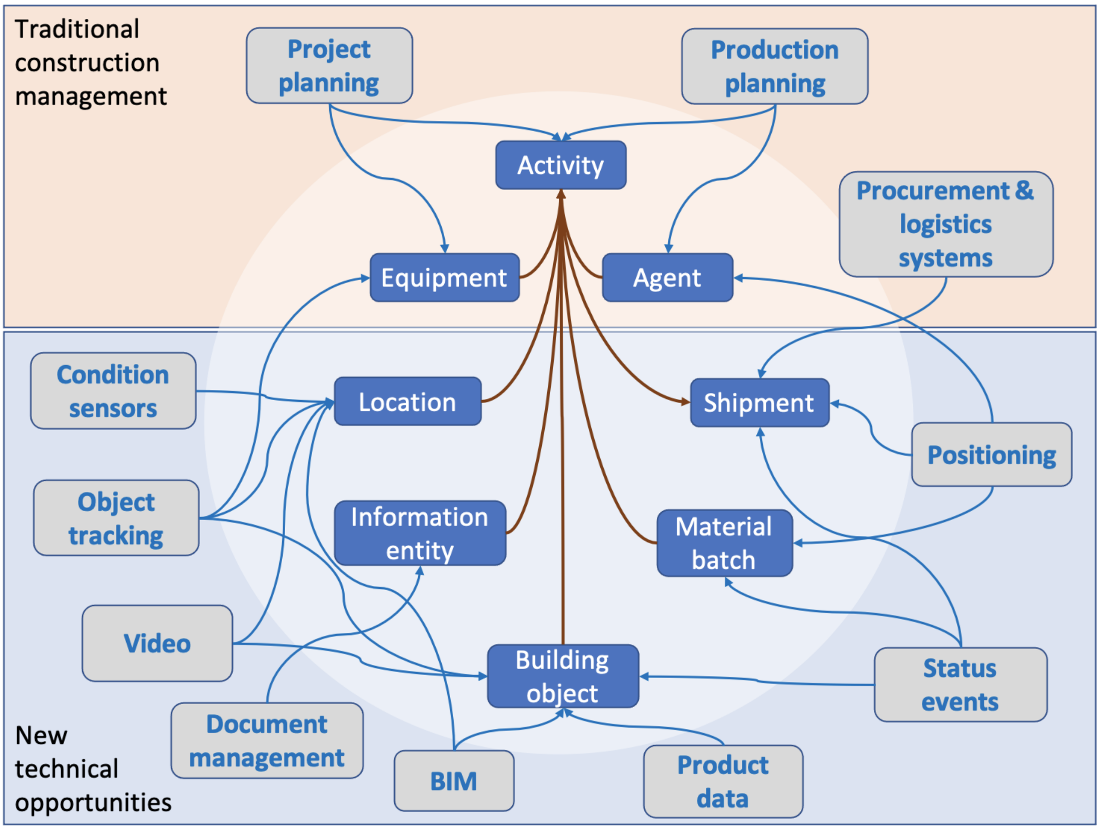

Figure 2: Central concepts of situation picture

The ontologies should also take into account the differences between the planned workflows and the actual workflows. The traditional way of recoding the actual times of planned activities is insufficient to support learning. The actual workflow often deviates from the planned workflow not just temporally but structurally: there can be additional activities in the workflow (cleaning, searching for materials and equipment), a switching order of activities (due to an obstruction preventing the planned order), or even missing activities. The recording of this kind of differences requires that the planned and actual workflows can be completely represented in different worlds or contexts.

2.5. Discussion

To form and maintain an accurate and high-quality situation picture – that would support the operational coordination of activities of different parties – is a long-term goal. Both the manual and automatic progress data updating practices needs to be taken fully into use. Detailed facts and observations are necessary for the creation of an accurate situation picture, even though they alone are not sufficient; interpretation, comprehension and projects are needed as well. There is still a need for significant advances in technology to properly interpret – often noisy or fragmentary – sensor data, or to process video and images to enable accurate recognition of building objects and their states.

In addition, the practices to produce BIM models with contents appropriate for situation picture (for instance, models that include spaces, zones, and systems) need to be adopted. The plans need to be developed in a manner that workers and other agents who use the situation picture are also connected to the activities that they are responsible for. This would allow the automatic extraction of the relevant aspects of the situation to each agent.

The ontologies and especially tools based on them are still in an early stage of development. Many ontologies are achieving a status as a standards – such as BFO, ifcOWL, SSN/SOSA, OWL-Time – but there are also several ongoing efforts to produce ontologies that might contribute to representation of situation pictures. However, a much more significant enabler would be the emergence and broader adoption of software development practices that utilize ontologies and graph-based data management.

3. Digital construction ontologies

3.1. Background

Information is vital for on-site teams to be aware of the actual situations of construction workflows (CWs), and their related resources and constraints. The increasing advancements of information and communication technologies (ICTs) in the construction industry provides an opportunity to automatically collect the information. The current implementations include Internet of Things (IoT) (e.g., Ibrahim et al., 2014; Dave et al., 2016; Soman et al., 2017), indoor positioning systems (IPSs) (e.g., Zhao et al., 2019), computer vision/image processing (e.g., Zou et al.,2005; Tuttas et al., 2016), building information models (BIMs) (e.g., Wang et al., 2014), enterprise resource planning (ERP) (e.g., Hadidi et al., 2017), and supply chain management (SCM) (e.g., Irizarry et al., 2012) systems.

Although these ICT implementations enable automatic information collection and provide large amounts of digital information and data, they are point solutions that cannot alone result in a comprehensive situational picture of the construction workflow. Therefore, a systematic integration of all the information from these systems based on construction domain knowledge should be explored to build a holistic situation picture of construction flow. The primary barrier to achieving integration is information heterogeneity. Information from related workflow entities is often acquired via various information sources and from different stakeholders working in their own construction disciplines using a variety of tools, systems, and software. To further increase heterogeneity, construction projects are characterized by different detail levels and commitment states of essentially the same information: there are multiple levels and versions of plans, and in addition to plans, there is the actual execution, there are as-designed and as-built models, and designs at several LOD levels, and so on. All this information needs to be preserved for further learning, and therefore there is a need to have a representational mechanism to manage this kind of multi-context data. In sum, due to heterogeneity, the information received from one system may not be comprehensible to other systems, resulting in insufficient interoperability between the systems to build a situation picture.

When facing such challenges, standard construction information models are required to achieve information management and system interoperability. Known as an “explicit specification of a conceptualization” (Gruber, 1995), an ontology can act as such an information model by effectively integrating heterogenous information by providing common unambiguous terminologies of concepts and relations based on domain knowledge with a computer-interpretable format (Karan et al., 2015). Furthermore, as the foundation of implementing Semantic Web and linked data technologies, ontologies could also enhance the sharing or reuse of information, data, and domain knowledge (Anumba et al., 2008).

In the DiCtion research project, we developed a suite of ontologies called digital construction ontologies (Dicon), where our goal was to offer a higher-level conceptualization and formalization of CW with shared and reusable domain knowledge representation. The ontology is novel in its provision of an unambiguous formalized information structure, which can serve as a reference to structure and integrate the data and information from multiple heterogeneous systems to build a situation picture of the construction workflow. The ontology suite will be valuable to both industrial users and academic researchers working in the lean construction, digital construction, and linked data domains, as it demonstrates how heterogenous information can be integrated and further utilized under the linked data framework to support construction management.

3.2. Development of ontologies

In this research, we have established a hybrid ontology development approach by taking the Uschold and Gruninger (1996), METHONTOLOGY (Fernández-López et al., 1997), and SKEM (Noy and Mcguinness, 2001) approaches into account as well as using the systematic framework for ontology building developed by Zhou et al. (2016) as references. The approach includes four stages, 1) specification, 2) knowledge acquisition/conceptualization, 3) implementation, and 4) evaluation (Figure 3). A series of monthly workshops were conducted with both ontology developers and domain experts to support the ontology development. The workshop participants included the internal members from consortium and external guests and experts. The participants represented different areas of construction (including designers, developers, contractors, software suppliers, precast concrete suppliers and steel suppliers) and had extensive experience and knowledge of the construction domain.

The aim of ontology specification is to explicitly specify the scope and purpose of targeted ontologies and to determine the intended users and requirements of the ontology. Based on the specified ontology scope and purpose, the functional requirements of the ontology are typically identified by using competency questions (CQs). CQs are a set of requirements, formulated as questions in natural language, that the ontology should be able to answer (Grüninger and Fox, 1995).

The next step is knowledge acquisition, in which relevant domain knowledge of the construction process was initially reviewed. Then, the conceptualization was conducted based on the knowledge obtained from the workshops and literature review. The major steps in this phase included listing the relevant terms in the ontology, defining a class hierarchy, defining class properties, and specifying the range and domain of the properties (Noy and Mcguinness, 2001).

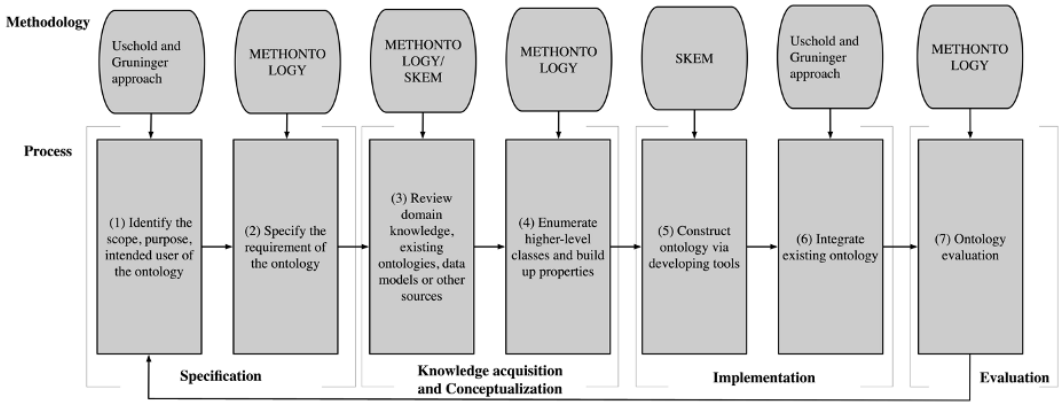

Figure 3. Ontology development approach

After conceptualization, the ontologies were implemented by defining them in OWL (Semantic Web Ontology Language) to flesh out their details, to enable automatic ontology reasoning, and to make them machine-readable for new, ontology-based applications and tools. The implementation and further refinement of Dicon ontologies was carried out in collaboration with the BIM4EEB project (H2020, #820660), including the definition of additional renovation-specific ontology concepts and modules. During the implementation phase, we also imported and mapped relevant external ontologies with the Dicon to improve its reliability and usage.

Ontology evaluation is the essential and final process in the development of ontologies. Based on the purpose of Dicon, we selected the following five evaluation criteria: clarity, coverage, consistency, extendibility, and usability. Accordingly, for this research we adopted a combination of automated consistency checking, expert workshops, criteria-based evaluation, the answering of CQs, and task-based evaluation to evaluate the ontology.

3.3. Digital construction ontologies (Dicon)

Figure 4 illustrates the ontological model of Digital Construction Ontologies (Dicon). Activity is the central concept, and different aspects of the construction process are associated with activity. In the ontological model, an activity was thus modeled as a process that has various entities as participants, also known as flows, including agents, material batches, equipment, locations, information content entities, and precedence activities. The object of an activity can be any entities that are the main focus of an activity. The terminologies of the classes and relations were set up by using prior models and ontologies reviewed in the knowledge acquisition phase. Meanwhile, the components of the CW (in the lower part) are also aligned with the top-level concepts from the Basic Formal Ontology (in the upper part).

Moreover, all the fundamental classes in the ontological model are combined as one entities module. To describe more detailed models of the workflow entities, including the agent, information, and process modules, these modules are further expanded based on the classes of agent, information content entity, and activity. The agents module illustrates the various concepts and relations to describe the capabilities, roles, and organization-related aspects of the CW. The information module was developed to provide an unambiguous description of CW-related information content entities. The processes module was used for representing the detailed CW. Besides these four modules that provide basic representations of the relations of activities and which entities are the ingredients of flows, the variables module was built to specify the state of an entity and also the condition of an activity. The context module was also included to represent multi-context data, which is an essential feature of Dicon. The context module is the conceptualization of different contexts, and the information of the entities in the various contexts is represented in certain named graphs.

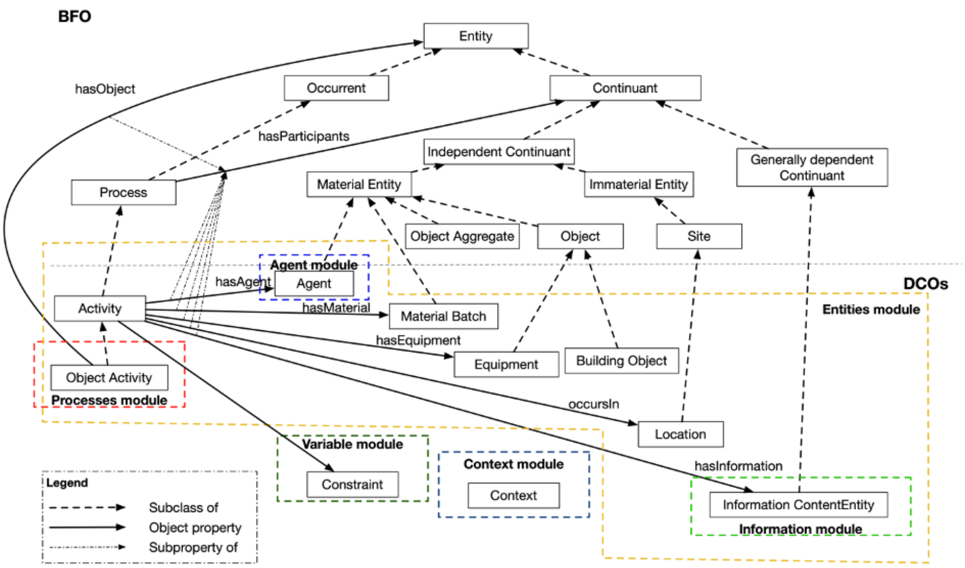

Figure 4. The ontological model

All the ontology modules were implemented in OWL. The ontology suite has also been published online, with the current version 0.3. Due to space constraints of this report, the detailed description of these modules is omitted, but their detail documentation can be accessed using the links in Table 1. And detailed description of the ontology development and evaluation are in the manuscript by Zheng et al. (2021).

Table 1. Ontology modules of Digital Construction Ontologies (Dicon)

Modules	**URL**	**Prefix**
Entities	https://w3id.org/digitalconstruction/Entities	dice
Processes	https://w3id.org/digitalconstruction/Processes	dicp
Agents	https://w3id.org/digitalconstruction/Agents	dica
Information	https://w3id.org/digitalconstruction/Information	dici
Contexts	https://w3id.org/digitalconstruction/Contexts	dicc
Variables	https://w3id.org/digitalconstruction/Variables	dicv

The standardized or otherwise broadly adopted ontologies that overlap with the domain of Dicon and that are used by Dicon as supplementary ontologies to give more detailed concepts and properties for entities they contain are the following:

- **IfcOWL** for the representation of BIM models; it provides the concepts for building structures, spatial elements, geometries, and property sets.
- **SSN/SOSA** and Saref for sensor information; targets of observations, observable properties, observations, sensors, and platforms of sensors.
- **QUDT** for units of measure, covering concepts of quantities, quantity kinds, units, dimension vectors, and datatypes for values.
- **OWL-Time** for time-related concepts and relations: time interval, time instant, duration, interval relations (before, overlaps, during, ...), and time datatypes.
- **FOAF/Org** for agents: person, team, organization, role, capability.
- **PROV-O** for the provenance of information: the origin of information and the processes, agents and tools involved in its creation.
- **BFO** for fundamental categories, such as process, material object, quality, information content entity, function, spatial region, and temporal region.

3.4. Use cases for situation picture

Two case studies were conducted in the research. These cases aimed to illustrate the capability of the ontologies in integrating the information and using instance data to answer the CQs, thus, to support the building of construction workflow situation pictures.

3.4.1 Case 1: Subcontract monitoring

In this case, Dicon was used to facilitate the interchange of heterogeneous information related to subcontract activities, to support the general contractor in tracking and monitoring productivity and quality related to a particular subcontracted scope. The original data sources were obtained from various systems, including: the construction schedule; the architectural BIM model; indoor sensor data on relative humidity and temperature; and quality inspection information.

The process to generate the linked dataset is shown in Figure 5. The distributed data sources were first mapped to the Dicon ontologies (shown in Figure 6) and then converted into RDF to instantiate the ontology. The converted RDF graphs were then aligned based on the common location element and stored in a triple store in the Graph DB tool together with the ontology. After the RDF graphs were stored, SPARQL queries were conducted with the aim of answering the specified task-based CQs to evaluate the ontology. Table 2 illustrates the results of SPARQL queries.

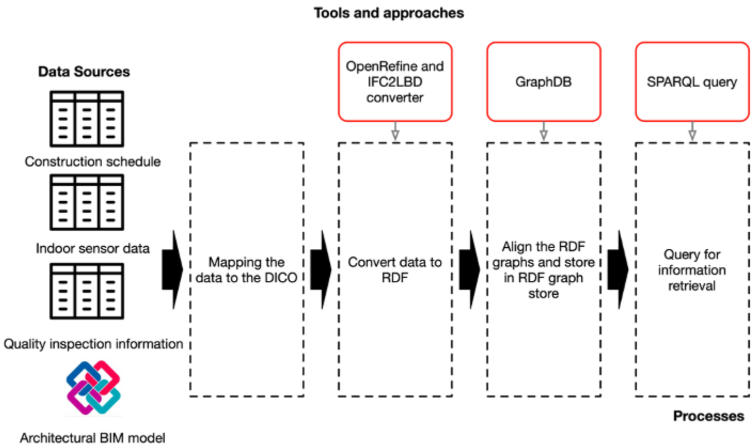

Figure 5. The process used to map the data sources to DICO

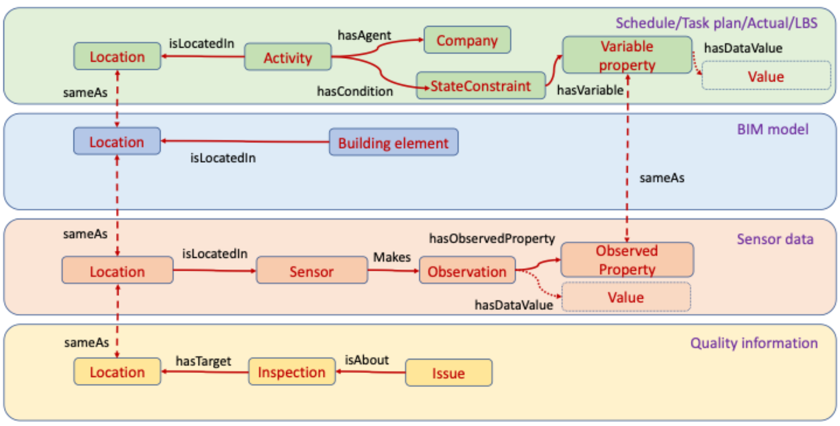

Figure 6. Mapping the information source to Dicon for subcontract monitoring case

Table 2. Specified CQs and answers based on the subcontract monitoring case

Competency questions	Answers
1. Where is the location of activity K31 Korjaukset?	Apartment 1, apartment 2, apartment 3
2. Who is responsible for this activity?	Subcontractor B
3. What is the status of the activity?	Completed
4. What is the UUID [universally unique identifier] of an activity location in the BIM model?	Apartment 1: 0IbHTptORoJ8h7CKZWLXuT Apartment 2: 3wsTBvMwh8JPHMp-Ccd8d4l Apartment 3: 0xWPBsQ6ILH8RCKYwmc1Z3
5. What is the inspection result of the location?	Apartment 1: completed; apartment 2: completed; apartment 3: completed
6. In a certain time period when activity KEINUL1_1_A was happening at the location, what were the sensor observation values at that location during that time period?	Temperature: 25 Relative humidity: 27.64%
7. Based on the sensor observation values at that location, is the activity able to be executed normally?	True

3.4.2 Case 2: Resource flow monitoring

The second use case involved resource flow monitoring. In general, tracking the indoor position of labor can be used to monitor working behavior and to analyze the productivity of a construction process (e.g. Zhao et al., 2019). This use case required the integration of data, including indoor positioning data; the architectural BIM model; and the project's construction schedule information.

The practical project involved a residential building project during the interior operation phase. The integration process (as shown in Figure 7) was similar to the first case, where the data from various data streams were first mapped with the new ontology (as shown in Figure 8) and then converted to RDF format. Later, the RDF graphs were then aligned and stored in graph store.

For the second case, SPARQL queries were developed to retrieve information related to the resource (labor, in terms of practical data). The CQs and the results are shown in Table 3.

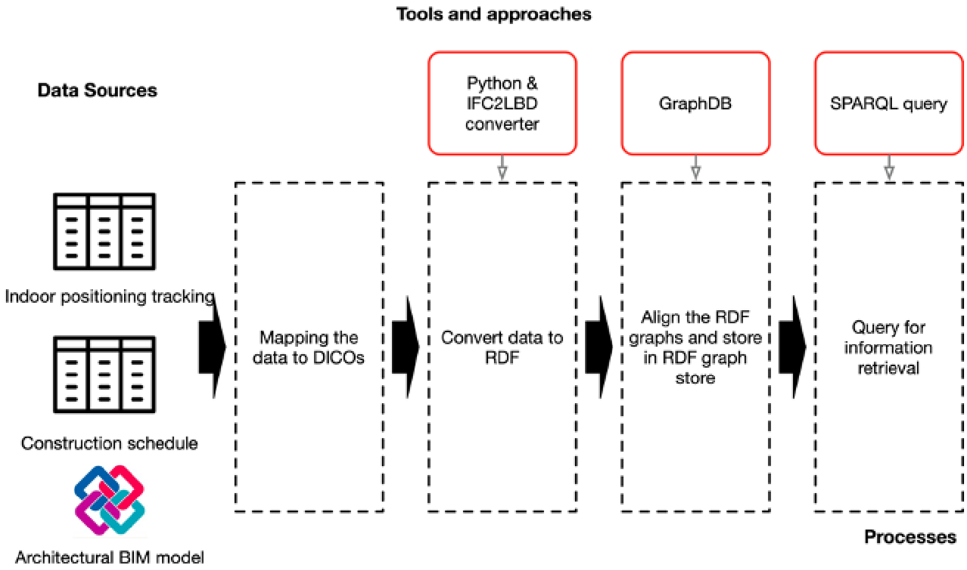

Figure 7. The process used to map the data sources to Dicon for the resource flow monitoring case

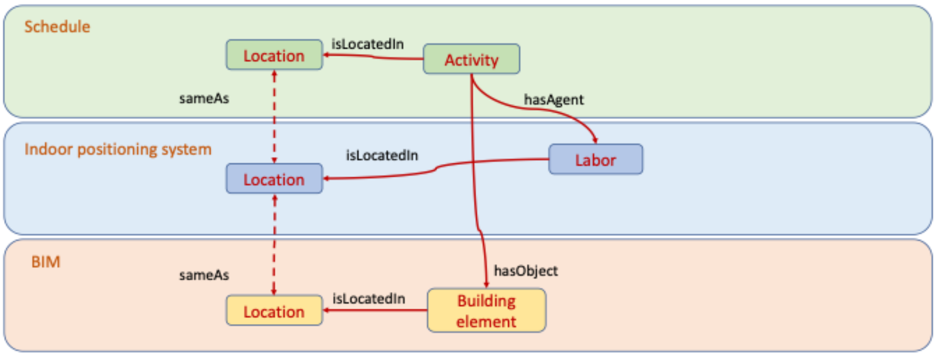

Figure 8. Mapping the information source to Dicon for the resource flow monitoring case

Table 3. CQs and answers based on the subcontract monitoring case

Competency questions	Answers
1. Where should carpenter 1 go to work on 15 June?	Apartment 3
2. Which activity is assigned to the carpenter?	Door installation
3. What building element is assigned for the activity?	Door 26
4. Was any labor done in apartment 1 from 1 p.m. to 2 p.m. on 6 June?	True
5. Who is in apartment 1 from 1 p.m. to 2 p.m. on 6 June?	Carpenter 1, carpenter 2
6. What is carpenter 1's trajectory on 5 June from 7 a.m. to 8 a.m.?	Entrance > staircase > apartment 1

3.5. Discussion

The two cases have illustrated that the Dicon was able to integrate the data from multiple digital systems. In the first case, the actual and as-planned information was stored in the different contexts to build up the integrated picture of subcontract workflows. The precondition of the activity was also represented by using the ontologies and could be used for comparison with the status tracking data to identify if variabilities could occur. In the second case, the integrated information from the IPS, the BIM model, and the schedule could support the workers and site managers in retrieving necessary information to support their jobs. These cases also showed that the integrated data could be used for further applications such as querying and information retrieval to support stakeholders to be aware of the situation thus to aid them make responding decisions.

4. Situation picture of the past and present

Accurate, shared situation picture is essential to make operational decisions. During construction phase, it has been very difficult to achieve this because the main *data acquisition* methods have been based on manual observations by project participants. These observations have sometimes been manually entered to IT systems (e.g. scheduling applications). The normal way has been to communicate status information socially, in either ad-hoc or recurring meetings where the status is also compared to plans and corrective action is planned. However, the manually obtained status information is partial, asynchronous and subject to biases by humans making observations. Although status information is communicated in meetings, there is no guarantee that every stakeholder in the project is making decisions based on the same situation picture. Recent technological developments could allow at least partially automated, real time situation picture to be generated and shared. (Soibelman et al, 2008; Zhong et al., 2015; Golparvar-Fard et al, 2012). While the previous work packages focused on integration of data from multiple sources, this work package looked at automating data acquisition and analysis with new technology.

Situation picture can be understood as integration between theoretical plans and actual progress on site. While the traditional process digitalizes information by human entry based on perceptions, new technology allows automated data acquisition by sensoring and computer vision and comparisons to theoretical plans. Situation picture emerges by comparing plans with reality and alerting decision makers of any deviations. Situation picture has a critical role because all the project stakeholders make decisions based on their knowledge of situation, which then impact the real situation in project environment. Figure 9 shows the theoretical plans (blue), actual situation (green), human-based situation picture (red) and automated situation picture (purple).

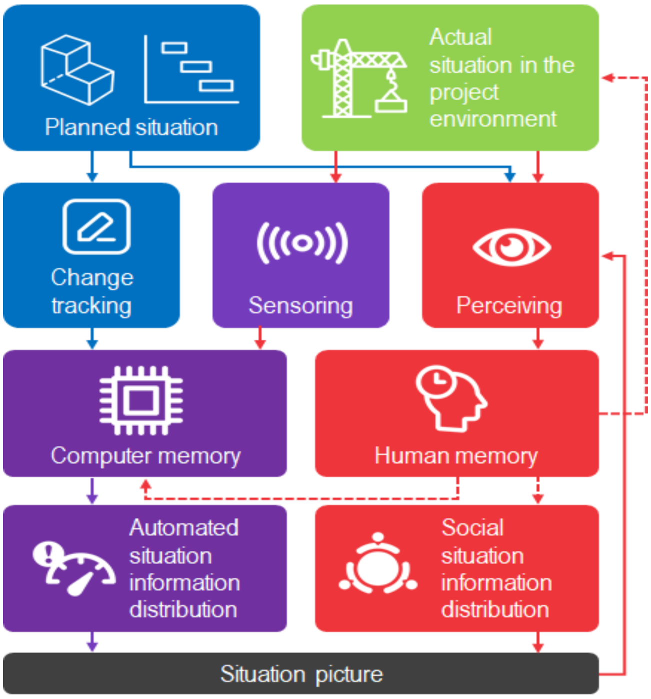

Figure 9. Creating situation picture socially vs. automatically (adapted from Kärkkäinen et al., 2019)

It is clear that sensoring and storing observations in computerized systems is key to achieving a shared situation picture that can be used to make decisions impacting the future. The same data can be used to analyze past successes or failures and to find root causes of problems for continuous improvement. However, the large amount of data coming from modern sensing systems, such as indoor positioning (e.g. Zhao et al., 2019) and computer vision (e.g. Khalid Masood et al., 2020) makes it difficult for decision makers and analysts to compose a situation picture from all the data streams. Comparing the situation to the planned context is critical but currently happens mostly manually in those projects where new data streams are collected. The problems of reflecting situation picture back to plans, defining new KPI's based on data streams and making machine vision scalable by combining multiple data sources were explored in this project. Highlights of results are presented below. More details can be found in the Work Package F report.

4.1. Combining data sources to increase power of machine vision

The project did not include any actual machine vision development but we devised a concept how multiple data streams could be combined together in order to solve the problem of drywall work progress detection. The drywall case was selected because it is an important scope in indoor construction in terms of share of project budget. Drywall has clearly visible states, suitable for vision-based analysis. However, the states cannot be evaluated by simply comparing captured geometry with designed geometry because the design typically shows each wall as a composite element without detailing all the work phases. In this case, the pure geometry-based detection is not sufficient. Therefore, our proposal combines both geometry and 2D visual comparison.

Drywall progress status can be classified in these consecutive classes:

- not started
- studs installed
- backboard installed
- in-wall electrical
- drywall closed
- wall plastered
- wall painted

Figure 10 shows example inputs and output of the proposed system. Video inputs, BIM models and schedules are the same for all use cases but the stage examples, as well as the system training must be tailored for each case separately. The top of Figure 10 shows some labelled drywall stage images. Often computer vision algorithms need thousands of labelled example images before satisfactory accuracy can be achieved, but this proposed system will be designed to be able to classify current states with minimal amount of example images. In Figure 10, there is also an example of the output. The contents of the outputs depend on the availability of supporting data sources, like existence of indoor positioning data (e.g., Zhao et al., 2019) or plans.

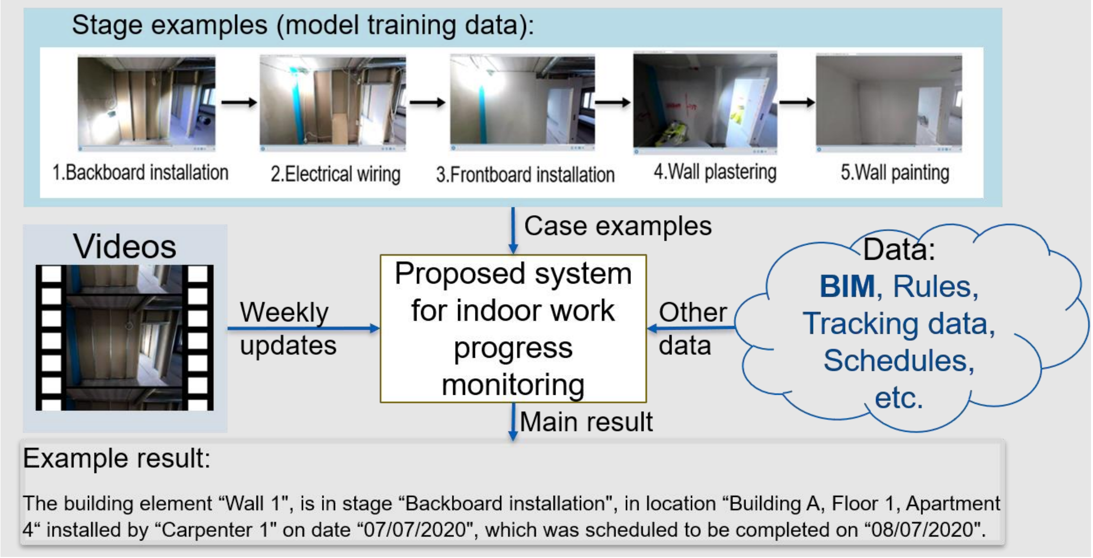

Figure 10. Main inputs and a result of the proposed progress detection system for the drywall case

The two necessary input data sources for this system are video recordings and the as-designed BIM model. Video recordings can be collected inexpensively by the site team and there are also commercial services available which provide indoor 360-videos. For our initial experiments we used data from 360 cameras mounted on helmets during weekly safety walk recordings. In order to match the video path and point cloud to designed indoor area, some context data is required to limit the search. A 4D BIM model could be used to filter out all elements which will be installed after the element of interest because they do not exist in the video material. For example, before drywall has been marked as complete, the comparison 3D model should not include floor coverings, fixed furniture floor covering material, or any doors attached to drywalls in question.

Other context data the system may use are Rules, Tracking data and Schedules. For the limited amount of the training examples, the visual analysis may benefit from the availability of some rules, like stage sequence order. For example, in the RECAP project (Seppänen et al., 2020), where bathroom and kitchen work progress were analyzed with computer vision, the use of stage sequence order yielded better classification result than classification without any sequential information (Byvshev et al., 2020). With indoor positioning data of workers, materials or tools, we can detect the active locations where work is most likely progressed. Tracking data and the schedules can be combined with computer vision result and this information can enrich the results as shown in Figures 10 and 11.

COMPUTER VISION

Which Ifc element?	Drywall 1
What stage of work?	Backboard installation

OTHER SENSORS (Ex: Bluetooth beacons)

What Location?	A-F1-ap004
Which worker(s)?	Carpenter 1
Start and End time?	*2020-07-07 T12:00* *2020-07-07 T16:00*

Figure 11: Fusion of computer vision and tracking data enabling productivity calculation by element

4.2. Task progress monitoring based on a real-time tracking system

In addition to computer vision, positioning technologies can be used as part of situation picture. Indoor positioning can be implemented with several technologies. In our research, we have used Bluetooth Low Energy beacons connected to Raspberry Pi gateways, but several commercial solutions exist. Our goal in this project was to evaluate whether location information in combination with schedule information would enable the automatic detection of task start and finish dates and potentially allow the detection of wasted effort between start and finish dates.

We collected data from one case study (detailed in WP F report and Zhao et al., *in review*) and by combining task precedence logic and information on which workers were working on which tasks, it was possible to estimate the start and finish dates of tasks based on indoor positioning information by looking at detected presence in work locations. Additionally, task-level presence indices (PI's) could be calculated by looking at the share of uninterrupted presence during the actual duration of the task. The results demonstrated that the schedules had a lot of waste because for most tasks the PI was between 25 and 40%, with the average being 34.4%. Between the start and finish dates, most of the work time the worker was not working in the location. However, the planned durations were achieved. Another important KPI was Presence-to-plan ratio, which shows how much presence was required compared to the original planned duration. This could be used to evaluate the share of buffers of planned duration. In the case project, the average task required 33.8% of presence to complete it in the planned time, so 66.2% of time was buffer. The results confirmed again that there is a huge opportunity to decrease durations of construction projects by removing interruptions of tasks and the proposed KPI's can result in real-time information which can help identifying productivity problems as they happen.

4.3. Heat maps for workspace detection using indoor positioning

In addition to looking at presence of workers at any given time and calculating KPI's based on uninterrupted presence, heat maps of presence could potentially be a useful method, especially when takt production is used. Heat maps could enable the calculation of actual work density. We experimented with heatmaps in this research project by conducting a case study with a Chinese partner. The full results are described in WP F report and in a conference paper (Zhao et al., 2020).

Due to issues with radio waves in complicated indoor spaces, any individual measurement can be off by several meters but the measurements tend to concentrate on the actual work space. Therefore, the heatmaps over a longer time period can give quite accurate view of patters of work. Heatmaps could be potentially used for analyzing work density and congestion. Work density is normally considered in the planning phase but indoor positioning technology enables continuous calculation and checking the assumptions of the plan with reality. Figure 12 shows hourly heatmaps of a mechanical worker in the case project which allow making conclusions about work area and even elements being installed because the area with most heat is matching with the actual direction of construction. Future research could include aligning the heatmaps with BIM models and making educated guesses of elements the worker is working on.

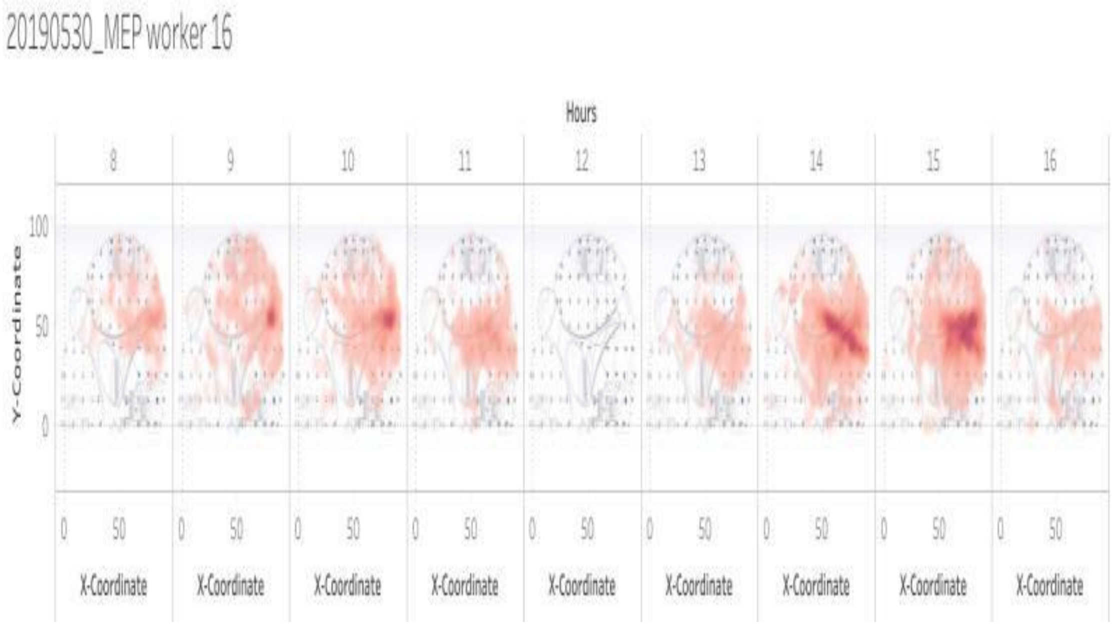

Figure 12: Heatmap of an electrical worker (Zhao et al. 2020)

4.4. Combined resource tracking of material and labor

Most earlier studies have considered either material or labor and analyzed them in isolation. In this project, we analyzed material and labor together. The case study is described in Work Package F detailed report. Our approach compared the uninterrupted presence of workers with the presence of material packs designated for each apartment. By comparing the share of time worker was detected with materials, without materials or with incorrect material pack, it is possible to evaluate the performance of logistics operations in the project. Although an advanced logistics concept (kitting) was utilized, the material kits moved several times during the project and workers were often working with materials assigned to another location or without any kit at all. The combination of material and labor tracking could therefore be used to measure the performance of the logistics system. It applies best to cases where larger containers of materials are delivered, although in our earlier research we have also piloted tracking every container.

4.5. Avenues for organizational learning aided by situational awareness

To systematically reap the benefits of acquired situational awareness, organizational learning over single projects, and even organizations is crucial. The provided situational awareness (for example, through real-time indoor monitoring systems) provides an unprecedented opportunity to accelerate the learning processes in construction organizations, which has not been previously possible. For accelerating organizational learning, we propose a conceptual framework that exploits the opportunities provided by situational awareness development. The model is based on a literature review and a study by Lehtovaara et al. (2019 b); a more detailed description of the construction of the model is presented in the WP F report.

The proposed framework (illustrated in Figure 13) consists of the following steps: i) production preparation that is based on organizational capabilities, ii) production control that employs single-loop learning through feedback collected from situational awareness tools, with iii) after-action review that employs double-loop learning by exploring the root causes of the observed issues, resulting in increased organizational capability for the following projects. The model has been developed and validated in DiCtion with one intervention and one validation workshop. Further validation is needed in future research.

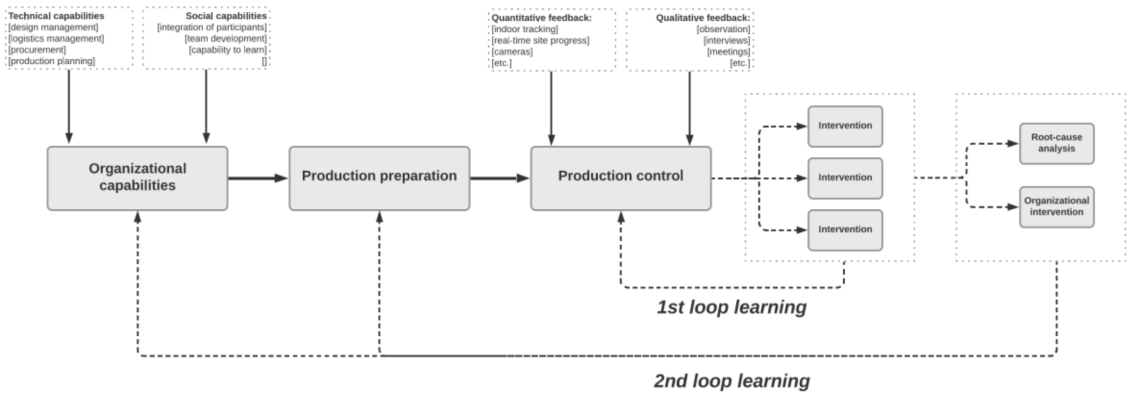

Figure 13: The proposed conceptual learning framework

4.6. Conclusion

Several automated ways to automatically sense the situation were piloted in the project. Interesting results were obtained especially related to automated detection of task start and finish dates and evaluation of logistics performance using indoor positioning combined with schedule information. Additionally, we proposed a scalable way to implement automated progress monitoring based on 360 videos. In the proposed approach, traditionally used machine vision approaches are combined with rich context data from other sources, such as indoor positioning or schedules using Digital Construction Ontologies. In future research, we will implement the proposed automated progress monitoring system and test augmenting progress monitoring with indoor positioning data. We will also use the KPI's defined in this project and conduct action research in real projects to help management achieve better outcomes using the proposed KPI's.

5. Situation picture of the future – collaborative planning approaches

5.1. Introduction

In addition to sensing workflow in the present and analyzing the past with KPI's, it is critical to have a shared understanding of what will happen next – the situation picture of the future. The goal of work packages B and C was to identify a common generic data model for creating, sharing and managing workflow data (WP B) and identifying new ways of planning (WP C). The work packages turned out to be tightly interrelated, so their results were reported in one report. It was necessary to start by looking at decentralized planning and how plans are currently done on different levels, to figure out what is critical on the data model side. By decentralization we refer to a process in which the decision-making authority is (at least partially) dispersed from central authority, such as from client and general contractor managers, to the individuals who are closest to the actual value-adding work, such as trade foremen and workers.

5.2. Social network analysis to understand the requirements

To explore decentralization in current construction planning and control practices, a case study was employed. The study involved a social network analysis (SNA) with several semi-structured interviews of project participants, such as production managers and trade workers. More detailed research design description is presented in WP B & C report, and in a study by Lehtovaara et al. (in review).

Even though construction production processes are traditionally managed through centralized processes, study results indicate that planning is realized in quite a decentralized manner. The decentralized nature of planning results in that even though construction production is managed with top-down processes, crew foremen and workers still tend to plan their work with limited attention to the master plan, or at least partially favoring their own preferences. The clash of these two partially contradictory approaches results, at worst, in a significant amount of waste and schedule unpredictability.

The most relevant knowledge needed for effective planning was indeed discovered to be held by the trade contractor foremen and workers. They were actively involved and mostly in charge of the final planning of the work, as well as managing the final design solutions, where possible. Designs were not usually detailed enough to serve installation, and thus the foremen and workers were often in charge of the final steps in the design management process.

The social network analysis also revealed that project participants from all levels of hierarchy believed that they made important decisions on planning their work and that people generally wanted to be involved in the planning process. The notion indicates that the foremen and workers do not necessarily need to be motivated for decentralized planning, but instead, better tools and processes should be implemented for them to be able to succeed in work planning as well as in the final design management.

However, in the project which was analyzed through SNA, it was indicated that the collaborative nature (several lean tools were utilized in the project) of the project enabled quite decentralized planning and diminished the clashes between the plans. However, the decentralized plan was not in a digital format. To achieve the vision of DiCtion, these individual plans of stakeholders should be able to be digitally collected and become part of the situational awareness of the project. Plans form an important part of situational awareness as demonstrated by Kärkkäinen et al. (2019) (Figure 9).

5.3. Common generic workflow model

In order to enable distributed work planning on a detailed level, a common generic data model for communicating the sequencing of work and dependencies between different construction operations is required. Because of findings related to decentralized planning by different parties, we adopted a novel approach by including the impact that different kinds of breakdown structures have on sequencing constraints. In the approach of Diction, different parties can have their own breakdown structures to group and decompose products, activities and resources. A specific goal is to enable the coordinated use of multiple different location breakdown structures during construction planning.

The concrete goal was to develop the Dicon ontology (WP E) to include a model of construction flows and their relations with activities. Different flows come from different sources, primarily from information related to end product and resources. A major source of end product information in the modern design practice are BIM models; component, material, workspace, and information flows arrive from that origin. There are also resource related flows such as labor, equipment and workspaces. It should be noted that workspaces have both an aspect of product information and resource information, depending on the activity.

To represent the relations of flows and activities it is not enough to know which flows relate to which activities. It is important to know the state of the flow that is required by an activity and that may be changed during the execution or at the completion of an activity. A key difference to previous methods is the explicit modeling of workspace as a resource. Each trade can plan using their own location breakdown structure and the logic in the data model allows detection of spatial conflicts which prevent work from occurring simultaneously. These spatial conflicts can be checked related to plans but also reviewed in real time by using situational awareness technology. Indeed, each one of the flows can be detected with situational awareness technology such as sensors, computer vision or design information, such as BIM. The detection of flows and activities enables a digital situation picture in construction. More details on the implementation of the data model can be found in the WP B & C reports.

5.4. Decentralized takt planning – a new collaborative planning approach

5.4.1 Motive for decentralized takt planning

As described in section 5.1, it turned out that construction processes are already now planned in highly decentralized fashion although most planning theories and systems assume centralized plan and control. The exception has been the Last Planner System which is highly collaborative but lacks a technical system imposing structure to the plans. Therefore, the most promising approaches look to be combinations of social (LPS principles) and technical (location-based principles), for example like described by Seppänen et al. (2010). However, rigidity is a fundamental issue in location-based methods – they assume a fixed location breakdown structure. In practice, the same locations do not work for all the workers who perceive locations differently. Another strand of research, of space planning, has tried to adopt the worker view by identifying in detail what kind of space requirements the task itself, its safety zone and its material laydown space require (e.g. Akinci et al., 2002).

However, there has been a practical implementation challenge that no one wants to preplan a project on that level of detail. Therefore, the technical system should be able to combine both bottom-up and top-down views of planning into one system. We approached the problem by conceptualizing a process of decentralized planning and control that would be connected to the flexible workflow models and also be able to further tested manually by the end-user companies, mainly by parties operating in production such as general contractors.

During the empirical studies, the process was determined to be connected to takt production, which has been successfully used to increase production flow through partially flexible location breakdown structures (e.g., Tommelein, 2017). Takt production has resulted in impressive results in construction projects in California (e.g. Frandson et al., 2013), Germany (e.g. Dlouhy et al., 2016) and Finland (e.g. Lehtovaara et al., 2019 a). These systems have been mostly driven in top-down fashion, except for the Californian model where trade contractor input is heavily used to direct the choice of locations. In any case, one set of locations is ultimately used for each contractor without considering explicitly the actual space need. Our proposed decentralized takt process goes to the level of space planning when coordinating specialists within the takt wagon, thus combining the bottom-up and top-down views of construction process.

5.4.2 Description of decentralized takt production process

To successfully utilize the decentralization in takt production, the main concern is how to exploit the operational knowledge of the foremen and workers during the planning and control processes. Implementing the rough frames for the plan from top-down, followed by bottom-up collaborative detailed planning offers a way to effectively combine centralized and decentralized ways to implement flow but also resource-efficient production plan. Moreover, the process attempts to reflect on the best practices to implement takt production (Lehtovaara et al., 2020 a, 2020 b) while also imitating the most optimal communication and decision-making patterns of decentralized production (Lehtovaara et al., in review). These practices, as well as the process itself are presented in more detail in the WP B & C report. The proposed process for decentralized takt production (figure 14) contains six steps.

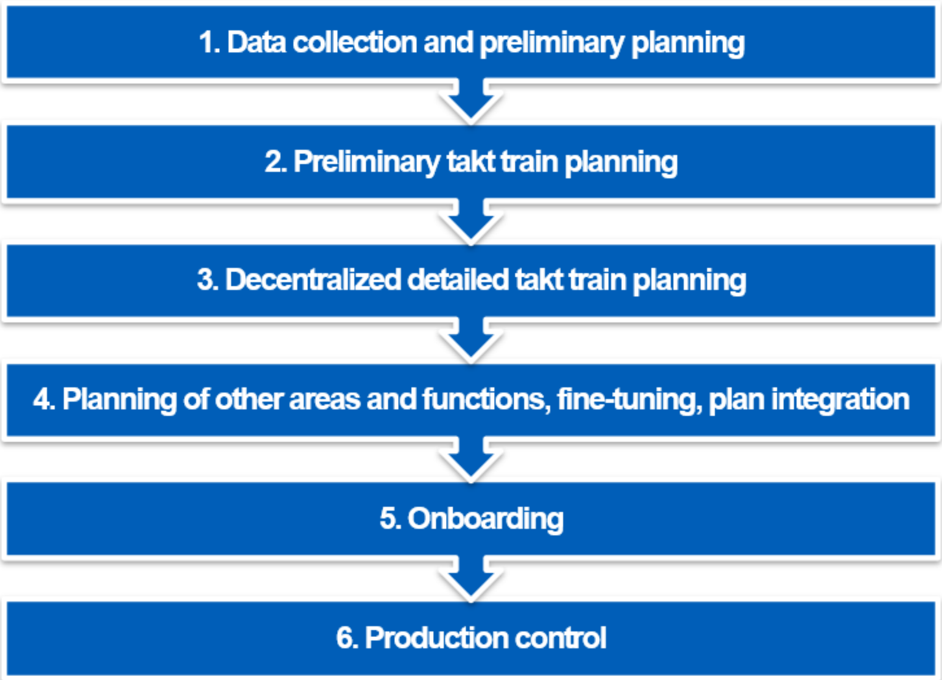

Figure 14: Situational awareness in construction (adapted from Lehtovaara et al., in preparation)

1. **Data collection and preliminary planning:** Necessary production data is collected, which forms a base for preliminary production planning. In addition, production scope and milestones based on the client's preferences, as well as defining rough functional areas and the fundamental production flow are determined. The first step is conducted by a 'core' team, including the GC project and site managers, client, and potentially trade contractors who have been involved early.
2. **Preliminary takt train planning:** Takt areas and takt time are defined simultaneously while defining work packages, wagons, and trains. This step allows to form the wagon-based teams to begin decentralized planning in phase 3. The second step is carried out with the same core team.

3. **Decentralized detailed takt train planning:** Planning teams based on the wagons are formed. The planning team, led by the trade foremen responsible for the works inside the wagon, also contain the participating crew members, material suppliers as well as designers related to the wagon (Figure 15). The teams continue developing the preliminary plan in a decentralized manner within the wagons, while also communicating the iterations with the core team and other planning teams.

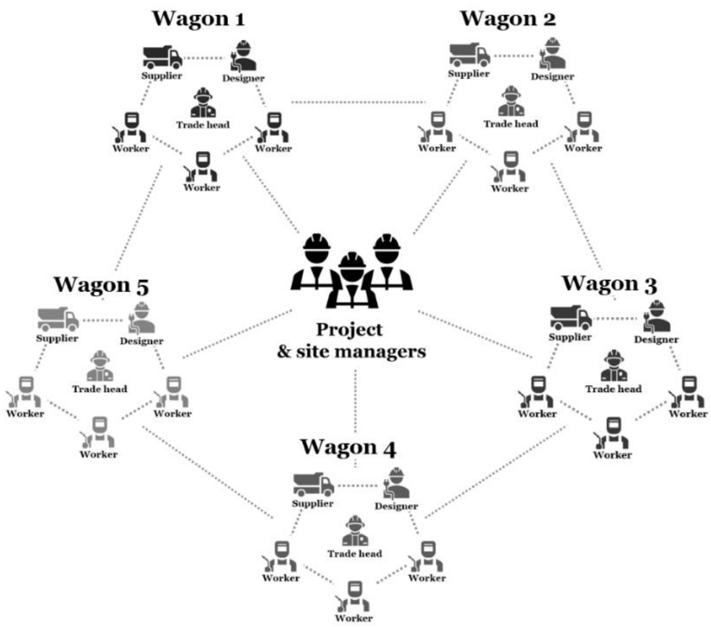

Figure 15: decentralized, wagon-based teams

4. **Planning of other areas and functions, fine-tuning, plan integration:** The plan is fine-tuned, for example, to match the worker resourcing needs. In addition, the overall plan is integrated into the major milestones to ensure that the production flow is in alignment with the requirements.
5. **Onboarding:** Production phase transitions and soft start to enable a smooth start in the first takts are planned. In addition, final design checks and logistics plan is coordinated between the parties to tackle any final issues before production begins.
6. **Production control:** Production control includes visual management with daily huddles (short meetings held every day), systematic quality control, and handoffs between wagons, as well as continuous improvement to tackle the emerged issues. During production control phase, constraints and their status are continuously reviewed based on situational awareness of the project and plans are updated based on current state of the production system.

In summary, the presented work aimed to construct a new process for decentralized takt production in construction. The constructed process was based on previous theoretical knowledge, knowledge developed at earlier work packages of DiCtion as well as on empirical research conducted through the research project. For further actions, the process should be manually tested by the end-user companies for validation. Moreover, further steps should include the attempt to digitalize the process as well as discrete event or agent-based simulations of the model to enhance the manual testing.

6. The link between supply chain management and situation picture

6.1. Introduction

The management of supply chains is problematic in construction. 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.

Successful construction supply chain management necessitates digital workflows. Digital workflows allow, e.g., advanced material logistics and the management of ETO products. This section discusses seven use cases for supporting digital supply chain management. The section presents the results received in work package D (WPD) of DiCtion research project. WPD work consists of three research streams, which all relate to creating a digital situation picture of construction workflows:

- **PART I. Digital workflows for supply chain management which concentrates on engineer-to-order (ETO) products. This work has been more thoroughly reported in conference papers (Lavikka et al., 2021; also Lahdenperä et al. 2021).**
- **PART II. Digital data flows in logistics which concentrates on make-to-stock (MTO) products. This work will be reported in two different scientific publications (Tetik et al., 2021; Khajavi et al., 2021).**
- **PART III. Requirements for inter-organizational deviation management process and system. This work is presented in this report.**

6.2. Digital workflows for supply chain management

We studied how digitalization could help in improving supply chain management. We focused on the supply chain management of prefabricated structural elements, which are engineered-to-order (ETO) products. Digital workflows could enable all project parties to know the up-to-date status of the construction site and better forecast into the future activities. For example, a better situation picture would allow understanding whether a need exists to adjust plans due to actualized deviations.

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 16):

6.2.1 Optimisation of the schedule of designing and producing elements

The element fabricator manages production at a 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.

6.2.2 Optimisation of the look-ahead planning

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

6.2.3 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.

6.2.4 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.

6.2.5 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.

6.2.6 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.

6.2.7 Issue management

Contractors' issues and claims 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.

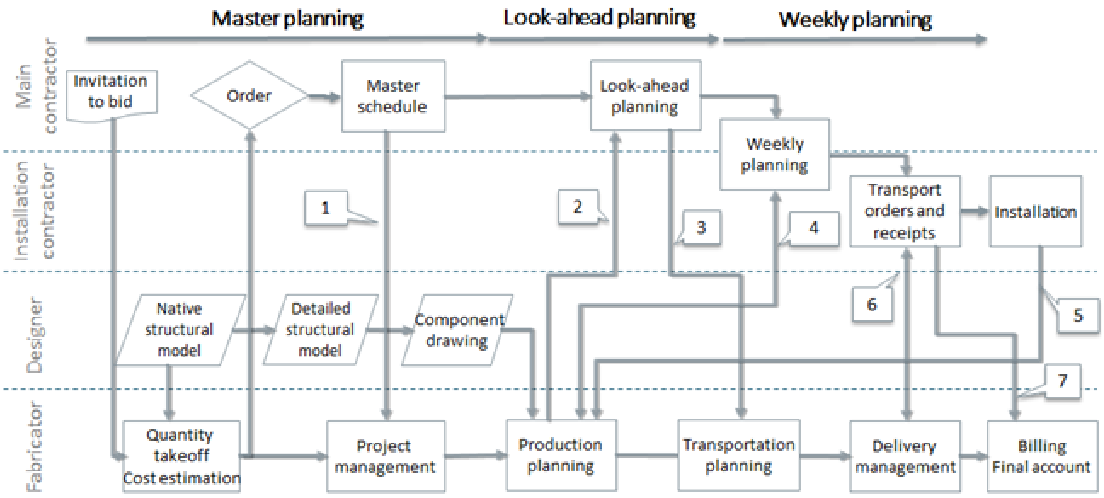

Figure 16. Digital dataflows of the seven use cases. (adopted from Lavikka et al., 2021)

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.

6.3. Digital data flows in logistics

As another use case related to supply chains of Make-to-Stock (MTS) products, we analyzed what kind of digital data flow would support using a kitting logistic solution. The kitting logistics involves the process of assembly kit packaging at the logistics centre, kits transporting to site, on-site unloading, and distributing to workplaces. Kits contain material and supplies needed in one assembly task in one location. Kits are used in workflow stabilization and productivity improvement as they move logistics work from assemblers to logistics service operators and enable assembly only in the planned work locations.

To work properly, kitting sets requirements for information management and its digitalization (Figure 2). 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 purchased commercial products should be linked to the elements of the digital building model. The element- and space-based BoM information combined with the digital planning information about the linked tasks would enable defining assembly kits with the specific BoM, 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.

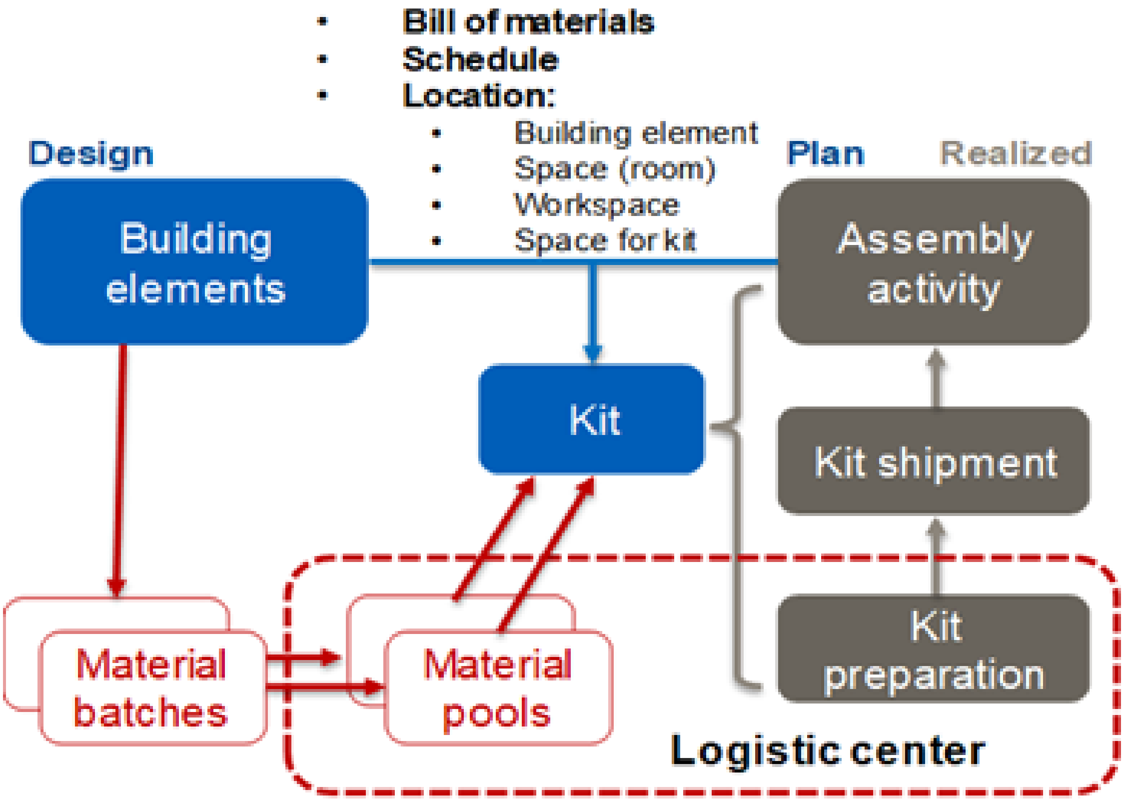

Figure 17. Requirements for digitalization: the kitting logistics process.

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.

6.4. Requirements for inter-organizational deviation management process and system

In the last part of the work package, we studied how construction industry could learn from digital information sharing regarding quality deviations of projects. Projects involve multiple organizations of which each typically focuses their quality activities in one part of the project using intra-organizational quality policies, processes and information systems. However, project-level quality management is crucial for the success of a construction project. In addition, as a result of current narrow-minded quality management practices, the industry is not learning together, and the same mistakes are made over and over again in new projects.

6.4.1 Inter-organizational digital deviation management process and its benefits

The researchers envisioned a process for inter-organizational issues management system (Figure 18). 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.

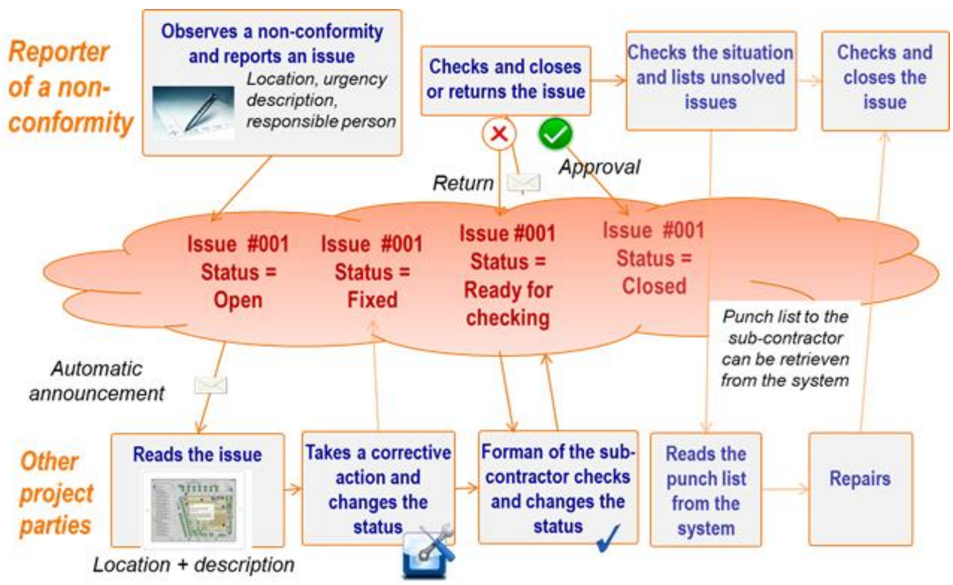

Figure 18. A process for reporting inter-organizational deviations in a cloud-based management system.

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.

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

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. 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. The data requirements for quality observations and non-conformities were 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.

At inspection stage, relevant data attributes include an inspection type/method (e.g. from quality control matrix), object of inspection, responsibility of the task under inspection, and participants of the inspection event. In addition to these, data regarding the observation should include fulfillment of a requirement (conformity/non-conformity), measurement result, and reference documents, such as images and quality requirements. In case of non-conformity, relevant additional data should contain non-conformity identifier, type of non-conformity (e.g. imperfect assembly/work, defective product), immediate cause of non-conformity, root cause and its description, type of planned correction, and responsibility, seriousness and due date of the correction. Finally, data regarding the correction process and impact evaluation contains attributes of financial responsibility, status of correction, type of made correction, cost and other impacts of non-conformity, free text about key learnings, reclamation information and references documents, such as bills and images.

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. 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.

6.4.3 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. In the trial software, the BCF REST API was utilized. Figure 19 presents the main data collections exchanged with BCF-API.

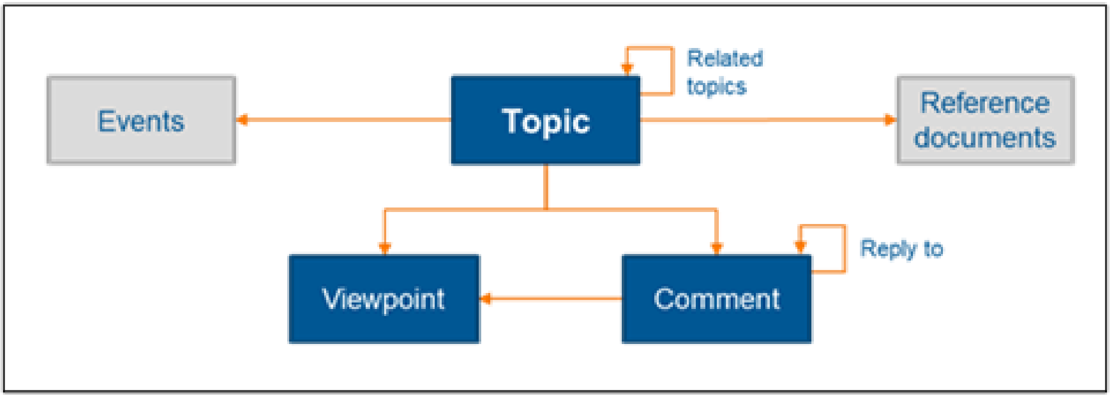

Figure 19. Main datasets of BCF-API specification.

The quality deviation data was transferred in BCF format between a software intended for site inspections and developed by Congrid Oy (https://congrid.com/) and Trimble Connect(https://connect.trimble.com/), 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 we tested an alpha-version of BCF-API (https://connectbcfapi.cloud.tekla.com/swagger/) implementation that in current setup converted BFC input as ToDos to show those in Trimble Connect user interface.

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. 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.

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 integral part of BCF is the reference to BIM as a Viewpoint dataset. It is possible in Congrid 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. A desktop application was implemented to test sharing inter-organizational quality deviation data.

As a conclusion, 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.

7. Business models and international validation

This section aims to shed light on possible revenue models based on linked data. The results originate from the work package G - Platform Model Enabling Global Business. The research work consisted of analysing already published articles and reports on linked data business models. In addition, two workshops were organised to discuss and verify the findings. The first workshop was organised on May 26th at the pre-event of WDBE ("Digital Situational Awareness", 2020). In addition to two facilitators, three participants, one from the USA, one from Oman, and one from Bangladesh, took part in the workshop. The second workshop was organised on October 23rd when twenty-five participants, representing the construction sector and academia, discussed the way forward with linked data.

7.1. Introduction

The performance of project management, decision making, and risk management could be improved with the support of data and information-based services. Furthermore, the European Green Deal steers the sector towards increased digitalisation ("A European Green Deal", n.d.). Many parties, such as architects, engineers, and managers, already produce and consume interdependent data during a construction project. Also, data are increasingly produced automatically by sensors and information systems. This means that data are and will be more and more crucial in the construction sector. In general, organisations sharing data with their partners usually generate three times more measurable economic benefits than those that do not (Logan et al., 2020). Hence, it is beneficial to start sharing data between organisations.

The development of advanced and novel algorithms and data analytics, which are used to improve construction projects' delivery, necessitate structured data from the various phases of the project delivery (Sacks et al., 2020). The acquisition of data is a challenge because construction project data are often in the format of files and stored in project banks from where data are not readily usable for sophisticated machine-to-machine data analysis. That is, poor interoperability is one of the main issues hindering the utilisation of advanced and novel algorithms and data analytics (Sacks et al., 2018).

Linked data technologies can be used for publishing, sharing and linking structured data inside or between organisations. Data, structured according to linked data ontologies, can be made available through semantic queries. The linked data provides a ready-made, standardised representation of building data and tools to improve the interoperability in the fragmented construction sector. As a technology, Linked Data builds upon standard Web technologies, such as HTTP, RDF, and URIs. While the regular web applies these technologies to help human readers to browse the web, Linked Data uses the technologies to allow computers to read data on the web automatically. In a nutshell, linked data refers to a decentralised environment, like the regular web, but it is meant for sharing machine-readable, structured data.

The use of linked building data could provide several benefits. It could reduce the multiple-handling of information, which would reduce costs and errors. Linked building data would provide structured data to develop and implement advanced and novel algorithms and data analytics. Additionally, this structured data could support business data analytics to design and create new services. However, although the linked building data technology has been proven to work in practice, viable business models based on linked building data are still missing. This was the motivation of this research.

7.2. The rationale for linked building data

In the construction sector, during different periods of the building life-cycle, many different software applications by many different parties and disciplines are used to create, organise, and manage building data. With the advent and implementation of, for example, building information modelling and sensor technologies, the volume of data to be managed has increased remarkably. However, data creation is often dispersed between different data sources, such as discipline-specific building modelling applications. Data exchanges rely upon the exchange of standardised file formats (e.g., Industry Foundation Classes) or the development of bespoke APIs (application programming interfaces). Hence, although these technologies have alleviated interoperability issues to some extent, the creation, organisation, and management of construction project information are still fragmented.

Poorly managed information, and different technologies and systems that are not properly aligned, resulting in manual double handling of information. If instead a linked data would be used to network the data across different data sources, then a lot of this manual double handling of information could be reduced. This would be achieved by avoiding interoperability issues, common in the current construction industry. Furthermore, it would be possible to automate many processes related to managing trade contractor relationships. For example, it would be possible to track the fabrication, transportation and installation of construction products and materials. Having the situational awareness of construction processes is required for the industry to increase its performance, which in turn, together with digital twins of the construction process could enable platform economies in the construction industry. New and novel services could be developed, which would help improve productivity and value creation. It would also bring benefits to software development companies and vendors because there would be limited issues related to exchanging data between different applications. The report of WP G describes additional use cases for linked building data.

7.3. Business model change is imperative

The older workforce in the construction sector is usually not yet tech-savvy, although differences exist between individuals. This older generation has not been educated to utilise digital tools in the management of construction operations. As a result, not all incumbents have realised that eventually, the software will be an integral part of construction operations, and long-term investments are needed to digitalise operations. Thus, some companies will fall behind, and some will go forward. However, the younger generation is accustomed to using digital tools, and that generation is already investing in new technologies and having transformation projects aiming at productivity leaps.

The construction sector is highly fragmented, and technologies in the current form, such as the BIM technologies relying on IFC, do not support the exchange of data in a seamless way related to life-cycle processes. Also, implementing the linked building data in the context of traditional business models may face challenges. Traditional business models in the construction sector are based on the idea that the competitive edge depends on withholding information and sharing with others as little as possible. In this context, companies are creating their own information systems, which often duplicate the information (classes, properties and relationships) in the original source by either manually transferring data or by using exchange file formats. This has often led to large, closed IT systems that try to solve the whole problem (e.g. ERP systems). Thus, a business model change is imperative in light of increasing digitalisation in the construction sector.

Implementing linked building data with construction ontology (such as Dicon) in this context would result in a situation that a decision needs to be made: which sources of data are more authoritative for specific classes (e.g., location, actor), properties (e.g., name, type) and relationships (e.g., contains, is_a subclass). Furthermore, if the information in respective dispersed software applications is changed, the question becomes which data is accurate.

To solve the problem of multiple data sources and versions, ISO 19650 defines the concept of a common data environment. This concept combines current thinking, technologies, mostly BIM-based, and workflows for managing project and asset information. Specifically, the ISO 19650-1 defines the common data environment as the “agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process” (ISO, 2018). This would alleviate the already mentioned problems but raises several other questions. Who is responsible for setting up the common data environment, who is the owner of the data, and how is the authorship of the data protected? According to the standard, it is the appointing party (client/owner) who should establish the common data environment for the construction project or the asset to be delivered and managed.

However, a better solution would be a common data environment utilising the linked open data and construction ontologies. This would help address all issues related to multiple data sources, versioning of data, ownership and authorship of project and asset data during the construction project delivery, and handover to the client. In other words, we need a digital twin of construction processes and assets. However, the problem is that such a technology does not yet exist. Here the startups may play a significant role. With the help of startup companies, a technological platform would have to be developed (Sacks et al., 2020).

7.4. Linked building data services and solutions

Technology service providers are probably the first ones to create services based on linked data in the construction sector. Several types of services, supporting data providers and users in utilising linked data, can be envisioned:

- **Linked Data Hosting – provide server capacity to store and access Linked Data.**
- **Linked Data Brokering – provide metadata about datasets to direct users to relevant data**
- **Linked Data Linking – generate, host and serve link sets between existing datasets**
- **Linked Data Backup Service – backup/cache link data to ensure uninterrupted access**
- **Linked Data Integrity Service – check data sources for broken, missing or changed links, validate data against data shape specifications**
- **Linked Data Access Control – manage user roles, authentication, authorisation, single sign-on, encryption**
- **Linked Data Aggregation – gather data into merged datasets for easier analytics**
- **Linked Data Analytics – use Linked Data for data analysis or machine learning**
- **Linked Data Adapters – tools to expose existing data as Linked Data through conversions or on-the-fly adapters**
- **Linked Data Consultancy – help companies to utilise Linked Data technologies**

Currently, only a few linked building data providers exist. The ones that have already been developed, such as the Trinity by GraphMatrix in the USA and Platform of Trust in Finland, are utilising the concepts and principles of linked data and construction ontologies. These technologies can be used to create and provide micro-services for different use cases, such as predictive analytics, automated tendering and facilities management. Linked building data and construction ontologies are especially useful in conducting activities and solving problems related to multiple domains, such as between trades, and data therein at the same time.

GraphMatrix exploits the Solid Foundation's technology to develop their own services. Solid is a project led by MIT Prof. Tim Berners-Lee, inventor of the World Wide Web. The objective is to change the way Web applications work today by providing true data ownership as well as improved privacy. It is a technology for organising data, applications, and identities on the web by building on existing web standards. Based on this technology, GraphMatrix provides several services in four application areas, including services for construction information exchange, productivity, facilities management and logistics handling.

Platform of Trust supports the integration, i.e., merging and utilisation, of incompatible data coming from various sources. The objective is to support the development of smart services and more comprehensive analyses for decision-making and new business opportunities by reducing cost and time related to the market. Platform of Trust does not collect data, but only provides the integration services using APIs. Customer can decide where data are stored, who can use the data, and for what purpose.

Currently, Platform of Trust supports data integration across various data products, such as humidity, temperature, CO_2 sensors, and data sources, such as Schneider EcoStruxure™, Granlund Manager, and AccuWeather. Platform of Trust is planning to incorporate Dicon ontologies (partly developed in the DiCtion project) for the construction phase.

7.5. Ecosystem and revenue models for providing linked data services

The provision of linked data services would enable the development of a 'Linked Data Ecosystem', consisting of various actors, such as linked data providers, data consumers, data brokers and regulatory entities (Archer et al., 2013). Linked data providers provide their data as linked data. In the context of a construction project, any actor could be considered as a data provider. Data consumers, also any actor in the construction project, reuse linked data for their and project's benefit. Thus, in a construction project, an actor can be both a data provider and a data consumer. (Archer et al., 2013)

Data brokers are usually third-party organisations that provide linked data services, such as data brokering, analytics, backup, integrity and access control. Data brokers may also provide services related to linked data use cases, such as linking product data to BIM, requests for information or changes, deviation/error data exchange, process and product analysis or information exchange to buildability and maintainability. Data brokers can provide market places for these services as well, often in the form of cloud-based service platforms (See, e.g., Lavikka et al., 2018). Finally, regulatory entities are usually national public administrations or transnational institutions, such as the European Commission, which regulate data exchange, through GDPR and other similar types of rules and regulations. (Archer et al., 2013)

In general, a business ecosystem's actions are based on trust and mutual benefit (Moore, 1996). In the construction sector context, the linked data ecosystem's shared goal could be, e.g., better quality construction processes and end-products (materials, buildings etc.). In the best case, the resources and competences of the ecosystem actors are complementary. The linked data business ecosystem would be founded on linked data technologies and tools, defined processes, plans, norms and rules. The ecosystem would be based on the interaction between organisations. The interaction would aim to create value to the customers; in this case, the construction supply chain actors. However, it must be noted that linked data technologies can also be used just to improve organisations' internal processes (Pellegrini et al., 2013). However, we claim that the use of linked data between organisations would bring more significant benefits to the whole construction sector.

Algorithms, Internet and cloud computing were the building blocks for the consumer web's revenue models. First, in the early days, the web content was free for the users, but the users had to get accustomed to the several ads included in the web pages they were browsing. This 'free for the users' business model was based on the processing of personal data. In sum, companies paid for the web page owner/service to advertise their products and services for the users. Later on, users had to get accustomed to subscription-based business models practised by web services, such as Yousician, Spotify, and Netflix, based on trust and consent-based data sharing. The benefit of subscription-based business models has been that the user does not have to watch ads and receive personalised services. For example, algorithms are used to recommend content based on the users' previous service actions.

The previous linked-data deployments, such as Linked Open Data Cloud, have been based on the use of encyclopaedical, governmental, geographical, life sciences or cultural data. However, most building data can only be shared among authorised users because there are physical security, data security, competition, IPR and privacy concerns (Novak & Tjoa, 2019). Linked building data requires role/actor-based authentication, authorisation, access control and single sign-on methods. Advertisement is not an applicable business model in machine-to-machine systems. Currently, no "proven" linked building data revenue models exist. One challenge is the extraction of value in a decentralised system. Another challenge is the definition of a control point/role that allows value extraction.

However, based on the consumer web's revenue models, similar types of revenue models could also be valid in case of linked data services. The data brokers could provide linked building data services applying the following three types of revenue models:

1. Service fees
    - Subscription in the form of periodical payments
    - Usage-based, for example, depending number of accesses, the number of links generated/served, and the amounts of data stored or transferred.
2. Freemium
    - Provide basic Linked Data services for free and do business with high availability/quality (backup/cache, reference integrity checking, usage statistics) and/or analytics applications based on linked data for a fee.
3. Outcome/value-based fee
    - Customer pays for a measurable outcome, e.g. “20% increase in productivity”. Note that in this revenue model, the risk is moved from the customer to the supplier. However, the parties can agree that compensation is provided to the supplier if he exceeds expectations.

Service fees and freemium types of revenue models are probable models for sharing and using data in the construction sector. It may be that the outcome/value-based fees will not be that popular, since a study revealed that the current business models of construction companies are too similar to enable outcome/value-based competition (Pekuri et al., 2015).

7.6. Discussion and conclusions

The implementation of linked data into the construction sector will take time. In general, new technology implementation is challenging as the parties who should use it, do not often understand the technology on a detailed-enough level. Also, for some companies, technology's cost is an essential factor in deciding whether to implement it.

One obvious solution is that data brokers, i.e., linked data service providers, show the construction sector parties how linked building data benefits them. One benefit of linked data is that data stays in the authors' ownership, although other parties can apply the data for the smart supply chain management. Another advantage is that linked data enables structuring data in relevant ways, allowing the use and creation of algorithms, thus, enabling automation and better data analysis. Still, viable business cases for linked building data in the construction context are missing. However, GraphMatrix and Platform of Trust, as examples, are data brokers that may start the transformation process towards applying linked data. The future will tell.

Companies need to change from ‘guarding their information’ towards ‘benefiting from sharing and integrating linked data’ to stay competitive in the era of digitalisation. The design and construction actors in the sector could collaborate with startups and accelerators of the data brokers, technology providers. However, most of the construction sector companies are at the beginning of their digitalisation road; these companies are only considering how to digitalise their operations. On the other hand, other companies are already trying and failing with business processes and business models. Only a few companies in the construction sector have changed their business model to better benefit from digitalisation.

In practice, several parties and actions are needed to boost the utilisation of linked building data and construction ontologies. Contractors could help create viable use cases by expressing their supply chain management challenges, which could probably be solved through better data analysis. Also, owners and general contractors need to start demanding the use of linked building data to receive better software interoperability. On the other hand, software providers need to begin using the linked building data technologies and construction ontologies. Co-creation between the software providers and construction-sector companies is needed to create software that fits the construction sector's needs. Linked data services could create a linked data ecosystem, consisting of data brokers, data providers and consumers. Regulatory entities are also needed in the ecosystem, ensuring that business is fair, and data is used according to GDPR.

8. Conclusions

8.1. Targeted outcomes

The project targeted kicking off digital transformation of construction industry by enabling efficient and transparent processes between the stakeholders. Creating a distributed situation picture of a construction project was the key technological target. In achieving the situation picture utilizing multiple data sources, Linked Building Data technology was identified a key element that requires ontology based information models for construction operations and workflows. As scientific outcome, the project aimed at 8-10 scientific publications in academic journals and several conference papers.

8.2. Distributed situation picture of a construction project

During the project, the consortium was able to define (Kärkkäinen et al., 2019) and also to partially achieve situation picture of a construction project. Fira, in collaboration with an ecosystem of start-ups, developed a situation view which combined data from various sources to a project-level dashboard and was able to significantly improve project outcomes (e.g. Alhava et al., 2018). VTT and Aalto researched the supply chain view of situation picture by integrating quality information of precast concrete operations (Consolis) with Fira's quality tracking system.

Aalto University developed ways of collaborative planning which were compatible with a new workflow model which allows tying automatic sensing to schedules and their flows. Although the distributed planning was not piloted during the project due to COVID-19 restrictions, the workflow model can enable significant steps forward in automating situation picture and reflecting it back to plans of individual stakeholders.

Individual data streams were also combined to see how integrating data streams from multiple technologies could benefit the creation of digital situation picture. For example, it was shown that by integrating indoor positioning systems to schedules, it is possible to automatically track start and finish times of tasks without manual entry required. Indoor positioning combined with logistics can measure the performance of the logistics system. By combining multiple data streams, computer vision can become a scalable solution.

8.3. Linked Building Data technology

One of the key research outcomes of the project were the Digital Construction ontologies. They were developed based on a series of workshops with consortium companies and feedback was received internationally in workshops at Stanford University (CIFE), TU Delft and two online workshops during COVID-19 with several participants from different countries. The ontologies are being implemented both by consortium companies and the ecosystem developed during the project to integrate solutions. We also identified potential business models for Linked Building data.

The ontologies were tested in practical cases by taking multiple data streams and successfully integrating them together to answer competency questions which were related to situation picture. Ontology was shown to help in integrating data sources. Companies of the consortium (Fira and Trimble) have used the ontology work to develop semantics of their software solutions.

8.4. Research outcomes

At the time of this final report, two journal articles have already been published based on the results of the research project. One of them continued the work started in RECAP project (Khalid Masood et al., 2020) and the other one presented the organizational learning model (Lehtovaara et al., 2019) that was later expanded to take into account situation picture. Three journal articles are currently in review process and three articles are in preparation and close to submission phase. The research has resulted in material for three additional journal papers which will be submitted and published after the research project. Although the final number of accepted journal papers is still unknown, we are well on track to achieving the academic goal of the project.

In addition to journal papers, several papers have been published in academic conferences. Presenting this work in conferences has started interesting international collaborations, especially related to Digital Twins of Construction which are enabled by the advancements of digital situation picture achieved in this project.

8.5. Future research

It can be said that it is now possible to achieve the digital situation picture and several companies have successfully developed commercial products around it. The next step is to provide data on the use of situation picture in order to start the digital transformation. The practical use of situation picture in projects is currently being explored by the Building 2030 consortium (www.building2030.com) which collects use cases and evidence of success from multiple case projects which implement different data collection techniques.

Technologically, situation picture enables digital twins of construction process. One natural continuation of this project is to link the situation picture to agent-based simulation models which enable continuous decision support based on current status of project. EU has funded the project DigiTwin and the researchers and some companies of this consortium are collaborating with the researchers of that project to increase the use of DiCtion results.

With situation picture and Digital Twin, we can start to think about process and machine automation. Automating deliveries to site, autonomous machines and robots and automatic creation of work assignments to people on site are interesting opportunities which are enabled by the advances of this project. Some steps are already being taken in this direction and several funding applications are in progress to accelerate research and development on this track.

References

A European Green Deal. (n.d.). Retrieved June 25, 2020, from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

Akinci, B., Fischer, M., & Kunz, J. (2002). Automated generation of work spaces required by construction activities. *Journal of construction engineering and management*, 128(4), 306-315.

Anumba, C. J., Issa, R. R., Pan, J., & Mutis, I. (2008). Ontology-based information and knowledge management in construction. *Construction Innovation*. https://doi.org/10.1108/14714170810888976

Archer, P., Dekkers, M., Goedertier, S. & Loutas, N. (2013), Study on business models for Linked Open Government Data. https://joinup.ec.europa.eu/sites/default/files/document/2013-11/Study_on_business_models_for_Linked_Open_Government_Data_BM4LOGD_v1.00.pdf

Byvshev, P., Truong, P. A., & Xiao, Y. (2020, February). Image-based Renovation Progress Inspection with Deep Siamese Networks. In *Proceedings of the 2020 12th International Conference on Machine Learning and Computing* (pp. 96-104).

Dave, B., Kubler, S., Främling, K., & Koskela, L. (2016). Opportunities for enhanced lean construction management using Internet of Things standards. *Automation in construction*, *61*, 86-97. https://doi.org/10.1016/j.autcon.2015.10.009

Digital Situational Awareness in Construction pre-event of WDBE 2020. (2020). Retrieved June 15, 2020, from https://kirahub.org/en/wdbe2020/pre-event-digital-situational-awareness-in-construction

Dlouhy, J., Binninger, M., Oprach, S., & Haghsheno, S. (2016, July). Three-level method of Takt planning and Takt control–A new approach for designing production systems in construction. In *Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction, Boston, MA, USA, sect* (pp. 13-22).

Endsley, M. R. (1995). Measurement of situation awareness in dynamic systems. *Human factors*, *37*(1), 65-84.

Fernández-López, M., Gómez-Pérez, A., & Juristo, N. (1997). Methontology: from ontological art towards ontological engineering. In *Ontological Engineering Spring Symp. Series*.

Forbes, L. H., & Ahmed, S. M. (2010). *Modern construction: lean project delivery and integrated practices*. CRC press.

Frandson, A., Berghede, K., & Tommelein, I. D. (2013, August). Takt time planning for construction of exterior cladding. In *Proc. 21st Ann. Conf. of the Int'l Group for Lean Construction*.

Garcia-Lopez, N. P. (2017). An activity and flow-based construction model for managing on-site work. *PhD Dissertation*. Stanford University.

Golparvar-Fard, M., Peña-Mora, F., & Savarese, S. (2012). Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models. *Journal of Computing in Civil Engineering*, 29(1), 04014025. https://doi.org/10.1061/(asce)cp.1943-5487.0000205

Gortney, W. E. (2010). *Department of defense dictionary of military and associated terms*. Joint Chiefs Of Staff Washington.

Gruber, T. R. (1995). Toward principles for the design of ontologies used for knowledge sharing?. *International journal of human-computer studies*, *43*(5-6), 907-928. https://doi.org/10.1006/ijhc.1995.1081

Grüninger, M., & Fox, M. S. (1995). Methodology for the design and evaluation of ontologies. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.44.8723

Hadidi, L., Assaf, S., & Alkhiami, A. (2017). A systematic approach for ERP implementation in the construction industry. *Journal of Civil Engineering and Management*, *23*(5), 594-603. https://doi.org/10.3846/13923730.2016.1215348

Ibrahim, M., & Moselhi, O. (2014). Experimental study of wireless sensor networks for indoor construction operations. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 31, p. 1). IAARC Publications. https://doi.org/10.22260/isarc2014/0109

Irizarry, J., Karan, E. P., & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in construction*, *31*, 241-254. https://doi.org/10.1016/j.autcon.2012.12.005

ISO. (2018). Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). *Information management using building information modelling. Part 1: Concepts and principles & Part 2: Delivery phase of assets. BS EN ISO 19650-1 & 2: 2018.*

Karan, E., Irizarry, J., & Haymaker, J. (2015). Generating IFC models from heterogeneous data using semantic web. *Construction Innovation*. https://doi.org/10.1108/CI-05-2014-0030

Kärkkäinen, R., Lavikka, R., Seppänen, O., & Peltokorpi, A. (2019, May). Situation picture through construction information management. In *10th Nordic Conference on Construction Economics and Organization*. Emerald Publishing Limited.

Khajavi, Tetik, M., Mohite, Holmström, J., & Peltokorpi, A. (2021). *Additive manufacturing in construction industry: feasibility of supply chain configurations* [Manuscript in progress]. Department of Civil Engineering, Aalto University.

Khalid Masood, M., Aikala, A., & Singh, V. (2020). Multi-Building Extraction and Alignment for As-Built Point Clouds: A Case Study With Crane Cameras. *Frontiers in Built Environment*, *6*.

Koskela, L. (2000). *An exploration towards a production theory and its application to construction*. VTT Technical Research Centre of Finland.

Koskela, L. J. (1999, July). Management of production in construction: a theoretical view. In *Proceedings of the 7th Annual Conference of the International Group for Lean Construction*. Berkeley, California, USA.

Lahdenperä, P., Kiviniemi, M., Lavikka, R. and Peltokorpi, A. (2021). Development needs on the way to information-efficient BIM-based supply chain management of prefabricated engineer-to-order structures. Proceedings of the 13th European Conference on Product and Process Modelling, ECPPM 2021. CRC Press.

Lavikka, R., Kallio, J., Casey, T., & Airaksinen, M. (2018). Digital disruption of the AEC industry: technology-oriented scenarios for possible future development paths. *Construction Management and Economics*, *36*(11), 635-650. doi:10.1080/01446193.2018.1476729.

Lavikka, R., Lahdenperä, P., Kiviniemi, M., & Peltokorpi, A. (2021). Digital Situation Picture in Construction–Case of Prefabricated Structural Elements. In *International Conference on Computing in Civil and Building Engineering* (pp. 943-958). Springer, Cham.

Lehtovaara, J., Heinonen, A., Lavikka, R., Ronkainen, M., Kujansuu, P., Ruohomäki, A., Örmä, M., Seppänen, O. & Peltokorpi, A. (2020 a). Takt maturity model: from individual successes towards systemic change in Finland. *In 28th annual conference of the international group for lean construction.*

Lehtovaara, J., Mustonen, I., Peuronen, P., Seppänen, O., & Peltokorpi, A. (2019 a). Implementing takt planning and takt control into residential construction. In *Proceedings 27th Annual Conference of the International Group for Lean Construction (IGLC), Dublin* (pp. 3-5).

Lehtovaara, J., Seppänen, O., & Peltokorpi, A. (2019 b). Improving the Learning of Design Management Operations by Exploiting Production's Feedback: Design Science Approach. *Lean Construction Journal*.

Lehtovaara, J., Heinonen, A., Lavikka, R., Ronkainen, M., Kujansuu, P., Ruohomäki, A., Örmä, M., Seppänen, O. & Peltokorpi, A. (2020 a). Takt maturity model: from individual successes towards systemic change in Finland. In *28th annual conference of the international group for lean construction*.

Lehtovaara, J., Seppänen, O., Peltokorpi, A., Kujansuu, P., & Grönvall, M. (2020b). How takt production contributes to construction production flow: a theoretical model. *Construction Management and Economics*, 39(1), 73-95.

Lehtovaara, J., Seppänen, O., Peltokorpi, A., & Lappalainen, E. (in preparation). Implementing decentralized takt production into construction operations through design science research approach. Department of Civil Engineering, Aalto University.

Lehtovaara, J., Seppänen, O., & Peltokorpi, A. (in review). Exploring decentralized production planning and control in construction from the viewpoint of workers. Department of Civil Engineering, Aalto University.

Logan, D., Rollings, M., Duncan, A.D., Jones, L.C. & Toncheva, A. (2020). *Survey Analysis: Fifth Annual CDO Survey — Growth Must Continue in Order to Achieve Real Impact*. https://www.gartner.com/en/documents/3982574/survey-analysis-fifth-annual-cdo-survey-growth-must-cont.

Lundberg, J. (2015). Situation awareness systems, states and processes: a holistic framework. *Theoretical Issues in Ergonomics Science*, *16*(5), 447-473.

Moore, J.F. (1996), *The Death of Competition: Leadership & Strategy in the Age of Business Ecosystems*, Harper Business, New York.

Nofi, A. A. (2000). *Defining and measuring shared situational awareness*. Center For Naval Analyses AlexandriA VA.

Novak, N. M., & Tjoa, A. M. (2019, March). Towards a business value framework for linked enterprise data. In *2019 IEEE-RIVF International Conference on Computing and Communication Technologies (RIVF)* (pp. 1-6). IEEE.

Noy, N. F., & McGuinness, D. L. (2001). Ontology development 101: A guide to creating your first ontology.

Pekuri, A., Pekuri, L., & Haapasalo, H. (2015). Business models and project selection in construction companies. *Construction Innovation*.

Pellegrini, T., Dirschl, C. & Eck, K. (2013). Linked Data Business Cube – Modelling Semantic Web business models. In *Share-PSI 2.0 Krems Workshop: A self sustaining business model for open data*.

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers*. John Wiley & Sons.

Sacks, R., Girolami, M., & Brilakis, I. (2020). Building information modelling, artificial intelligence and construction tech. *Developments in the Built Environment*, *4*, 100011.

Seppänen, O., Ballard, G., & Pesonen, S. (2010). The Combination of Last Planner System and Location-Based Management System. *Lean construction journal*.

Seppänen, O., Xiao, Y., Khalid Masood, M., Byvshev, P., Pham, T., Aikala, A., & Lundström, P. (2020). Reality Capture (RECAP) project final report.

Soibelman, L., Wu, J., Caldas, C., Brilakis, I., & Lin, K. Y. (2008). Management and analysis of unstructured construction data types. Advanced Engineering Informatics, 22(1), 15–27. https://doi.org/10.1016/j.aei.2007.08.011

Soman, R. K., Raphael, B., & Varghese, K. (2017). A System Identification Methodology to monitor construction activities using structural responses. *Automation in Construction*, *75*, 79-90. https://doi.org/10.1016/j.autcon.2016.12.006

Tetik, M., Peltokorpi, A., Seppänen, O., & Holmström, J. (2021). *From Amateur to Excellence: Maturity Levels of Industrial Logistics Practices in Construction Projects* [Manuscript in progress]. Department of Civil Engineering, Aalto University.

Tommelein, I. D. (2017). Collaborative takt time planning of non-repetitive work. In 25th Annual Conference of the International Group for Lean Construction.

Tuttas, S., Braun, A., Borrmann, A., & Stilla, U. (2016). Evaluation of acquisition strategies for image-based construction site monitoring. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *41*, 733-740. https://doi.org/10.5194/isprs-archives-xli-b5-733-2016

Uschold, M., & Gruninger, M. (1996). Ontologies: Principles, methods and applications. *Technical Report-University Of Edinburgh Artificial Intelligence Applications Institute Aiai Tr*.

Wang, W. C., Weng, S. W., Wang, S. H., & Chen, C. Y. (2014). Integrating building information models with construction process simulations for project scheduling support. *Automation in construction*, *37*, 68-80. https://doi.org/10.1016/j.autcon.2013.10.009

Zhao, J., Seppänen, O., Peltokorpi, A., Badihi, B., & Olivieri, H. (2019). Real-time resource tracking for analyzing value-adding time in construction. *Automation in Construction*, *104*, 52-65. https://doi.org/10.1016/j.autcon.2019.04.003

Zhao, J., Seppänen, O., & Peltokorpi, A. (2020). Applying Heat Maps to Define Workspace in Construction Based on Real-Time Tracking System With Coordinate Positioning Information. In *Annual Conference of the International Group for Lean Construction*.

Zhao, J., Pikas, E., Seppänen, O.& Peltokorpi, A. (2021). *Using real-time indoor resource positioning to track the progress of tasks in construction sites* [Manuscript in review]. Department of Civil Engineering, Aalto University.

Zheng, Y., Törmä, S., & Seppänen, O. (2021). *A shared ontology suite for digital construction workflow* [Manuscript in review]. Department of Civil Engineering, Aalto University.

Zhong, R. Y., Huang, G. Q., Lan, S., Dai, Q. Y., Chen, X., & Zhang, T. (2015). A big data approach for logistics trajectory discovery from RFID-enabled production data. *International Journal of Production Economics,* 165, 260–272. https://doi.org/10.1016/j.ijpe.2015.02.014

Zhou, Z., Goh, Y. M., & Shen, L. (2016). Overview and analysis of ontology studies supporting development of the construction industry. *Journal of Computing in Civil Engineering*, *30*(6), 04016026. https://doi.org/10.1061/(asce)cp.1943-5487.0000594

Zou, J., & Kim, H. (2005, December). Image processing for construction equipment idle time analysis. In *Proc., 22nd Int. Symp. on Automation and Robotics in Construction*. https://doi.org/10.22260/isarc2005/0030