# Diction – Prerequisites for digitalizing construction workflows

## Overcoming the productivity problem in construction

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# 1. Introduction

Productivity in construction industry in the last few decades has not noticeably improved. During the same time period, other industries, such as manufacturing and agriculture, have digitalized their operations and achieved remarkable productivity gains. Why has construction industry not been able to achieve the same results although most of the large construction companies have invested heavily in digital tools, such as Building Information Modeling?

It looks like most of the attempts at digitalization have aimed at increasing the productivity and quality of office work, such as digitalizing change handling process using project management systems (e.g. Procore, Prolog), improving coordination and visualization of design (BIM software), optimizing schedules (scheduling software) or creating better estimates based on BIM models (e.g. model-based estimating software). Digital tools entered the site operations relatively recently and have been mostly point solutions to tackle specific problems. For example, schedule progress can be entered on a tablet on jobsite and it immediately updates the schedules of other stakeholders, or quality and safety issues can be recorded based on site observations. These tools have had limited impact, because they are still not measuring the operational performance of the project but are mostly related to project management functions. Digitalization that could impact the worker's productivity would require digitalizing material flows, information flows, equipment flows as well as previous work, in order to have an optimal starting point for the worker to do his/her work when he enters the location.

Currently, this optimal starting point is not achieved. Previous studies show that workers spend a lot of their working time moving from location to location to collect materials, find equipment or find information. This kind of "scavenging" behavior does not happen in manufacturing plants, where digitalization makes sure that the workers have everything they need when it is time to do their task. We are missing the critical ingredients for productivity improvement: the ability to ensure that all the identified eight flows required for productive construction are digitalized: labor, materials, equipment, external conditions, design information, process information, space and preceding tasks (Koskela 2000).

In order to ensure flows, real time information of construction process is required and workflows need to be digitalized. Recent advances related to Internet-of-Things technology and reality capture can provide situational awareness data. Technically, there are few obstacles. Technology to achieve situational awareness exists, although commercial providers have not created solutions tailored for the special aspects of construction industry. There are point solutions, but they are not currently integrated to form a situational awareness. The main obstacles are socioeconomic in nature. There is a general lack of trust between stakeholders and most used contract forms do not support transparency. Digitalization of operations will result in transparency which is actively opposed by many actors. The goal of this document is to explore these obstacles more deeply and propose ways to circumvent them.

This document will first present the current state of digitalization in construction, which the researchers have observed during the DiCtion - digitalizing construction workflows - research project (2018-2020). Then, the researchers discuss the social, business model and technical prerequisites for digitalizing construction operation workflows. Finally, the researchers will present future ideas for developing construction operations. The development ideas consist of new methods for construction operations, such as kitting, but also of digitalization efforts related to construction ontology development and its implementation.

## 2. Current state of digitalization in construction

Construction is project-based business where in each project a new type of product is being built through a process negotiated by the project parties not familiar with each other. Several stakeholders, such as the General Contractor and trade contractors are often selected based on a competitive bidding process. As a result, learning to work together takes time and mistakes happen more often when compared to off-site construction where construction resembles process-based manufacturing. Standardization and digitalization of work processes is challenging in such an environment where a new team of actors from several different companies are assembled together for each project.

Onsite construction work is often performed mostly by specialist trade contractors who are proficient in their work but who face challenges when the discipline boundaries between the different trade contractors are not planned. Building information modelling (BIM) has enabled the coordination of different design disciplines' work in the virtual world. However, the modelling tools are not yet capable of understanding what it takes to construct the design in the real world. Hence, sometimes workers are provided with designs that require the workers' expertise to understand the steps to construct the design. The general contractors rarely possess deep knowledge of the work that is ultimately done by specialized trade contractors. As a result, every trade contractor manages their own workflow and the general contractor is obliged to coordinate this fragmented construction workflow in order to get a functional end product based on these individual pieces.

Lots of construction work remains hidden from the general contractor, and thus coordinating and controlling the work of trade contractors is challenging, if not impossible. The general contractors have no efficient methods to follow the progress of the work onsite as there is currently limited digital data on the work progress. Applications to report progress by the workers exist (e.g. Fira SiteDrive) but they are not yet consistently used. Earlier research also shows that self-reporting is inaccurate because workers often forgot to update progress or enter progress information in batches later resulting in inaccuracies and a lack of real-time situation picture (e.g. Goodrum et al. 2006; Costin et al. 2012). The most common way to get a situation picture of a construction process today is by manual updates of scheduling software based on site visits or daily or weekly reports by subcontractors. This manual data processing is inefficient, costly and does not result in accurate situation picture. Scheduling software packages can calculate forecasts of future work but they are rarely used by contractors.

Progress entry is just one example of categories where digitalization falls short. Current trend has been that every time there is a problem, it is solved with a new smartphone application which is a point solution to a specific problem. These apps have emerged for safety, quality control, punch lists, tracking of issues, visualizing BIM models and for various other purposes. These tools do provide the means for collecting digital data from onsite activities, which is a prerequisite for making decisions based on data. The challenge with these point solution tools is that they are often incompatible; data cannot be transferred between the tools because data is stored in different databases in different formats. A common ontology that would define a common model for data sharing is missing, although IFC has to some extent made BIM models interoperable.

Next, we will discuss the social, business and technical prerequisites for digitalizing construction operations.

## 3. Social and business model prerequisites

Implementing digital tools on site will result in greater transparency. Unfortunately, many of the current contract forms are not transparent and thus digital technologies are often opposed by parties who feel that they could reveal mistakes and make project parties more vulnerable to claims. Some companies have business models that are actively benefiting from the lack of transparency, especially in the traditional design-bid-build environment. New digital tools have been implemented fastest in contract forms which require transparency, such as alliance and IPD contracts. In other contract forms, it looks like the Owner must have an active role and require greater transparency for digitalization to happen. Otherwise, just the currently used tools which enable tracking design issues and documenting delays are likely to be quickly implemented. New tools, such as indoor positioning and reality capture tools and potential for automated activity recognition and analytics seem to require high levels of trust between stakeholders.

Trust is a key prerequisite for shared, digital situational awareness in construction sector. Digital situational awareness requires the sharing of data between project shareholders and documenting the entire site with images and recognizing activities of workers. The data combined from various sources can enable a great productivity leap in construction process. However, there are a lot of opportunities for misusing such data. For example, all mistakes are clearly visible and cannot be easily explained away. Today's process is based on blaming others for mistakes but with situational awareness the real root causes of problems will be revealed. This enables continuous improvement but can also be used to attack the party who made a mistake. If the systems are used in this way, there will be heavy opposition. The same applies to the relationship between the construction tradesmen and employers. If situational awareness data is used to just increase supervision on site and workers do not get any benefits, labor unions will start to actively oppose the new technologies such as resource positioning and machine vision. There is potential for all parties to benefit but there is a big risk if the systems are used without win-win for all honest actors. Because lean construction aims to continuously improve the process, involve the supply chain more in long lasting partnerships and values the workforce, lean projects could be the best projects to start implementation.

The key obstacles for implementation are social in nature. Both superintendents and trade contractors work to suit their specific interests. Each party has optimized their process based on currently existing tools. Any new tools can unbalance the system and all parties could see that they are penalized in order to benefit the other party. Benefits of situational awareness will benefit all parties, if everyone changes their behavior at once but does not work well or results in unbalanced benefits if only part of the actors change their behavior.

For example, many trade contractors base their initial bid on efficient workflow and if their profitability is at risk, they can resort to claims which they base on excuses of others harming their productivity (Freeman and Seppänen 2014 called this the excuse backlog). They tend to try to maximize work-in-place to get a positive cash flow for projects. This behavior leads to cascading problems to other trade contractors but is optimal in traditional contract settings. Only if the trade contractor can trust that all other trade contractors and the General contractor will care about project first, the situation can be changed. (Freeman and Seppänen 2014). If digital situational awareness is entered into the picture, it will be harder for trade contractors to build the excuse backlog when everything is transparent. It is easy for General Contractor to validate exactly what happened after-the-fact. With current business models, many trade contractors may see situational awareness technology as a large risk – especially for those trade contractors who are early in the process and cause more problems to others than suffer from problems caused by others. The benefits may be unevenly distributed to the parties.

Superintendents are not used to manage based on data but rather make most of their decisions based on intuition and experience. An informed process based on data would decrease the perceived value of their experience. They prefer to react to current problems, rather than planning ahead. In their relationship with the Owner, they want to convey perfect understanding of the project. Superintendents think they can hold all the details of the project in their head and Owners are used to being able to make decisions immediately based on superintendent's knowledge (Freeman and Seppänen 2014). Real time situational awareness could cause problems to the superintendent because it could show problems that the superintendent was not aware about. It also would allow the Owner and the head office to look in detail at the production process and find issues which would decrease the authority of the superintendent. We have already seen examples where situational awareness technology was removed from the site after it became apparent that safety was not on as good level as claimed by the superintendent.

To create trust and willingness to transparently share data requires understanding the other parties' motives and business models. It is necessary to define how parties behave in a traditional setting (Construction 1.0) and how they should behave with digitalized workflows and situational awareness (Construction 2.0). This way all parties know what is expected of them in terms of behavior and how digitalization will actually impact their business. They will also see the list of current behaviors and learn to look for those and are more confident in notifying others about bad behavior. Peer pressure could be used to drive change. Although collaborative contract forms could benefit most because they already work to increase trust between project parties, any contract form could benefit if trust can be built between actors.

Data ownership also becomes an issue. Each party that can produce data that is potentially useful to other parties or the overall execution of a project, is faced with a complex decision balancing the costs involved in data generation and sharing, the value of data to the others, and the risks involved in data generation. The party that generates data obviously has - according to the principle of *data sovereignty* (IDSA, 2019) - the ownership of it and can decide with whom to share it, with what mechanisms, and what should be the compensation. For instance, data cannot be expected to be pooled into a common service for everyone to access, without an agreement with or among data producers. There can also be fine-grained issues regarding who can be granted access to which parts of data. A party may be willing to share operational data with other project parties but not necessarily with its competitors within a project. This means that there is, in the minimum, a need for a proper authentication, authorization and access control infrastructure. Moreover, there is a need to limit the risks related to data sharing, which should be addressed already in contracts among parties.

Before construction sites can leap forward in digitalization, these social prerequisites should be addressed. More understanding of opportunities and threats of digital technologies is needed to avoid resistance. Resistance mostly arises from lack of understanding, therefore understanding should be spread first so that companies have time to adapt their business models. Transparency offered by digital technologies is especially well suited to support the implementation of lean philosophy, so the implementation of digital workflows could start from those companies who are already building long term partnerships and are used to having open books with their customers.

# 4. Technical prerequisites

Although many of the prerequisites are social, there is still a lot to do technically. Point solutions for various applications, ranging from BIM tools for design and engineering, quantity surveys, and product data management to systems for construction management, logistics, positioning, condition monitoring, and augmented reality, are already being widely used in construction but have failed to provide a holistic situational awareness of project status. Each of these systems is typically targeted to human users and almost invariably stores and manages its own data using its own proprietary data model.

When digital systems are being increasingly adopted, increasing demands for machine-to-machine interoperation between these systems will arise. It is wasteful and error-prone for a human user to input the same information to multiple systems (when there are overlaps in their information contents), or to act as an intermediary between systems (when one system needs to refer to an entity managed in another). Many of the interactions between systems could be automated if there is sufficient interoperation between them. The benefit would be higher productivity and quality of information processes; moreover, when human users are released from being intermediaries between multiple digital systems, their capabilities can be put into more productive use. Ultimately, a completely digital, real-time situation picture could be realized by connecting a lot of data streams from different interoperable systems. First steps have been taken by implementing virtual control rooms but presently they require manual linking of proprietary data models.

## Levels of interoperability

There are multiple levels of interoperability problems: technical, syntactic, and semantic. The technical level means the communication infrastructure that allows the bits and bytes to be exchanged between systems in an unambiguous manner. The potential problems range from having no real access to the data at all to the limitations caused by restricted interfaces or complex security mechanisms. Currently, the Internet provides a practical communication infrastructure and the system vendors have recognized the necessity of providing proper interfaces to other systems. Moreover, the use of standard security solutions - such as OAuth 2.0 - is widespread which makes interoperation across systems more effortless. Accessibility between systems is a necessary precondition for any interoperation, and it is dependent on the readiness of companies to expose the data or functions of their systems and willingness to invest into development of the interfaces or data export/import functionalities.

At the syntactic level, a system that receives data may not be able to process it in the format supplied. It could, for instance, be in a proprietary binary format. This problem is currently being solved by standard data formats such as XML, JSON, and CSV. Indeed, if anyone provides an API to their systems, the use of any data formats other than standard ones would require good justifications.

Most of the difficult - and presently even open - interoperability problems are at the semantic level. The semantics concerns the meaning of the data in exchanged. What is the type of an entity? What relations and attributes it has? What are the types of related objects, or datatypes of attribute values? How is the identity of an entity specified? In the typical practice, these questions are decided in each system differently and, furthermore, they are coded as simple strings. Machine-to-machine communication cannot be based on data specified in such an ad hoc manner; in operational systems there is the need to know exactly the types of entities, their relations and attributes, and types of those.

The problem in the semantic interoperability is heterogeneity. Due to the idiosyncrasies resulting from human or technical origin there is pervasive variability of terms used in different systems. Even when same terms are used, their meanings can be different (homonymy). One of the most difficult problems are terms that mean almost the same but have also significant differences (polysemia). Another type of problem are caused by terms that are different and mean the same thing (synonymy). To solve these important semantic interoperability issues, a common language is needed.

## Ontologies for semantic interoperability

A solution to semantic interoperability problems are ontologies. An ontology is a specification of a conceptualization (Gruber, 1991), a shared definition of the terms (types and properties) in a domain. The goal of ontology development is to produce computational ontologies, that is, ontologies with computer understandable definitions that would enable machine-to-machine processes.

There are many ontologies available and large projects to develop ontologies to new domains. Typically, to capture the concepts of a larger domain, a suite of several complementary ontologies is needed. An example is the Open Biological and Biomedical Ontology Foundry (OBOFoundry), whose core is the successful Gene Ontology and that contains tens of interrelated ontologies. An approach to organize larger collections of ontologies is to have a top-level ontology that defines the fundamental categories of objects. An ISO standard for top-level ontologies is the Basic Formal Ontology (BFO), also used by the OBOFoundry. There are other large ontology efforts also based on BFO, such as the Industrial Ontology Foundry (IOF) and European Materials Modeling Ontology (EMMO). However, there exists also specific reference ontologies for clearly limited areas, such as temporal domain (OWL-Time) or unit of measurement (QUDT).

In construction domain, the ontology work has started from BIM models. A standard ontology for BIM models, based on the IFC schema, is called ifcOWL (Pauwels and Terkaj, 2015). It follows closely the structures of IFC; its definition is a set of conversion rules from IFC. There are converters that can translate the BIM models exported into an IFC file into an RDF graph using the terms defined in the ifcOWL.

To capture the information related to the execution of construction projects, additional ontologies are required to represent agents, activities, roles, capabilities, information entities, sensor devices and sensor data, time, units, and so on. A pervasive phenomenon in construction projects is the existence of multi-context data. The same data is represented in different context, such as planned and actual times of activities, as-designed and as-built models, models in multiple levels of detail, and so on. The Digital Construction Ontologies (DICO), an ontology suite developed in Diction and BIM4EEB projects, has been designed to capture this range of concepts.

Much of the actual use of ontologies requires solutions to translate data between application data schemas and the classes in ontologies. The translation can be a batch operation (such as the conversion of IFC file to an ifcOWL-based RDF graph) or it could be done on the fly, when the data is accessed. Which solution works better depends on the kinds of data and the usage patterns of relevant applications.

In summary, the solutions for interoperability problems at the lower levels - technical and syntactic levels - are known. Interoperability issues at those levels are currently being solved, although at the present implementations are still missing in many cases. However, the situation may be much better already after a few years. The difficult problems whose solutions are still in development are in the semantic level. Ontologies are a solution for semantic level interoperability. There are existing ontologies available to represent buildings, construction management, and sensor data. The adoption of ontologies requires the development of converters or adapters to the data of existing systems.

# 5. The end game – digital construction workflows

To motivate actors to tackle the technical and social prerequisites, we will present here use cases that could be achieved in the short or medium run through data interoperability and willingness to share data and that could substantially improve the production process. The opportunities are endless, so we have selected a few use cases that have been emphasized in the DiCtion project. The use cases relate to achieving a digital twin of processes for construction, solutions for industrialized logistics, collaborative planning of future task based on situational awareness and digital workflows for supply chain management.

## 5.1 Digital twin of processes for construction

The objective of developing and implementing a construction digital twin is to use the data collected through automated monitoring and sensing to plan, simulate, predict and evaluate the alternative courses of action and their possible consequences in order to make informed decisions. That is, the digital twin could be used to digitally represent the project operating system, on which hypothesis and ideas, for example, related to the layout and organization of the production system, could be tested through simulation.

Construction digital twins can be broadly divided into two categories: product twin and process twin. Much research on digital twins in construction has focused on the performance of physical assets, whether it is a component, asset, system (e.g., façade (Khajavi et al., 2019) or network of systems (e.g., energy performance of buildings (Kaewunruen et al., 2019) and their control. However, during the delivery of a facility, in design and construction, the product does not exist. That is, there is a need for different conceptualizations and models for product and construction production twins.

The digital twin for construction processes has three main elements: a physical artifact (built product and performed process), a digital counterpart (planned product and process), and the connection that binds the two together. For connecting the digital and physical counterparts, the flows of productive resources, including labor, material, equipment, locations, and information, and the progress of as-built building must be sensed in close to real-time (Kärkkäinen et al., 2019). However, most state-of-the-art applications for the simulation of construction processes are developed based on the planned (e.g., design decisions) and assumed parameter values. Although the parameter values may have been calibrated based on the empirical data or experimental data, the values are not connected to their physical counterparts, which is required to achieve the construction digital twin. In effect, the achievement of the digital twin of processes requires an automated sensing system which can be connected to simulation.

To achieve automated situational awareness, we must **acquire** sensor data holistically, **align** the data with design and planned information accurately, and **reason** on the aligned data robustly and reliably to infer the state of production.

Many advanced data acquisition technologies have been adopted into construction. Recently, helmet-mounted cameras were proposed (Pučko et al., 2018a), which capture the worker's environment free from occlusions and in a continuous manner, thus allowing progress to be monitored at regular intervals. However, current systems for monitoring and sensing construction products (as-built), processes (as-performed) and resources (labor, material, equipment and location) on and off-site are limited to specific construction subjects (e.g., the performance of the tower crane, heavy equipment management, safety), largely in outdoor environments (Kopsida et al., 2015). No single system provides a holistic view of all construction activities, both indoor and outdoor. In combination with UAV and crane cameras (Masood et al., 2019), these technologies could provide visual data for both indoor and outdoor environments. When integrated with position information from BLE beacons (Zhao et al., 2019), holistic data acquisition can be achieved.

A prerequisite to robust reasoning on visual data is the alignment of as-built and as-designed data, and the comparison of as-performed and as-planned construction production (flows of productive resources). Significant advancements have been made in aligning BIM models with images (Asadi et al., 2019; Han et al., 2018) and point clouds (Kopsida and Brilakis, 2020), but full automation in real-time remains an open challenge.

Reasoning stands as the grand challenge of sensing systems. Despite much progress in data-driven approaches such as Deep Learning in object recognition, robust and reliable scene understanding remains elusive, since deep learning techniques are poor at abstraction (Marcus, 2020). An emergent paradigm in Artificial Intelligence (AI) is the neurosymbolic system (Alirezaie et al, 2019), which combines classical AI approaches that are strong at abstraction with machine learning techniques that can learn from data. Here ontologies become critical so that data can be collected in uniform way from many projects.

Achieving the digital twin of processes also requires the development and implementation of a simulation model/engine that can take the standardized representation (construction process digital twin), populate it with as-performed and as-built parameter values (based on the advanced sensing information) and manipulate it according to pre-established rules. Such a digital twin system could work on two levels: product and process and use the process information to automatically coordinate design and production processes (Figure 1). Although several parts of the twin exist, such as advanced sensing systems and mobile apps for coordination, we are still missing a comprehensive, scalable and robust sensing system able to cover most tasks in construction site, a simulation model capable of taking in that information and optimization algorithms operating on top of that digital twin.

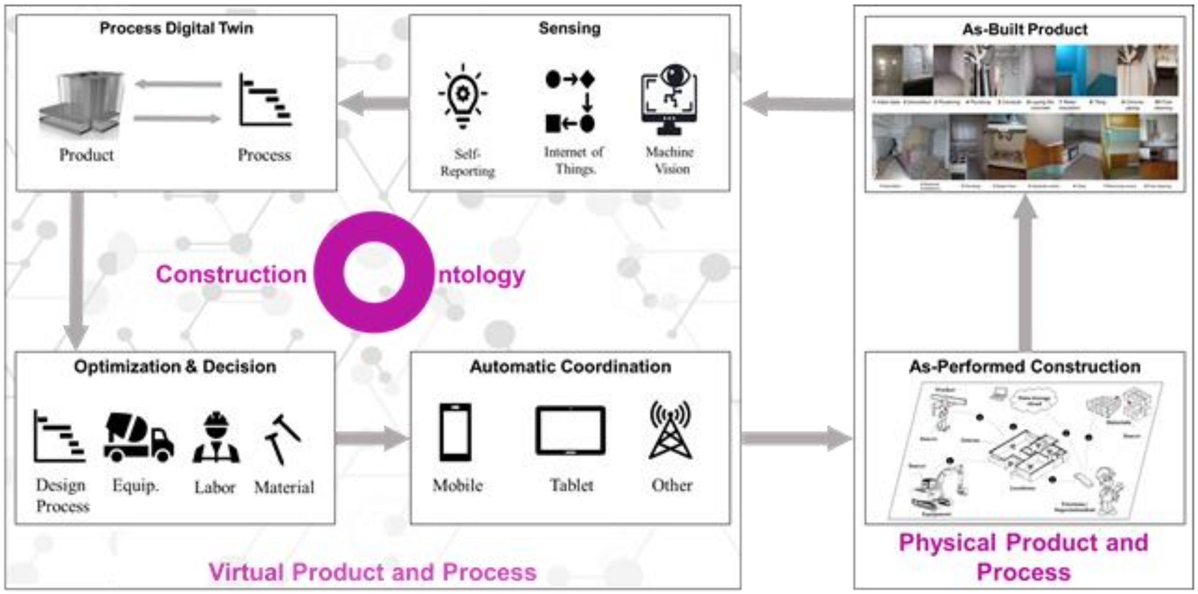


Figure 1: Digital Twin of Construction process could enable automatic coordination of construction stakeholders

The business models would have to change if digital twin of construction process could be achieved. Optimization and automatic coordination would take away many of the tasks currently manually performed by the General Contractor. It is possible that this kind of technology could enable platform economies in construction, partially replacing the General Contractor with a coordination platform relying on the Digital Twin. We expect to see considerable progress in this area in the next few years (2021-2025) and full pilot implementations by 2025.

## 5.2. Industrialized logistics

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

The kitting logistics process involves the process of material delivery, kits preparing/assembling at the logistics center, kits transporting, on-site unloading and distributing (shown in Fig.1). First, the material batches are delivered to the logistic center by suppliers. Then the workers in the logistic center should follow the material bill that indicates the required constituent material types in each assembly task and the quantity of the materials to prepare the kits. After the preparation, the kits are assembled as groups/packages of these materials and ready to be shipped to the construction site with a short lead time. These kits are typically location-based (provide the materials for designated location), task-based (for designated task), and time-based so that they can contain e.g. all materials needed in working two days in a renovated bathroom.

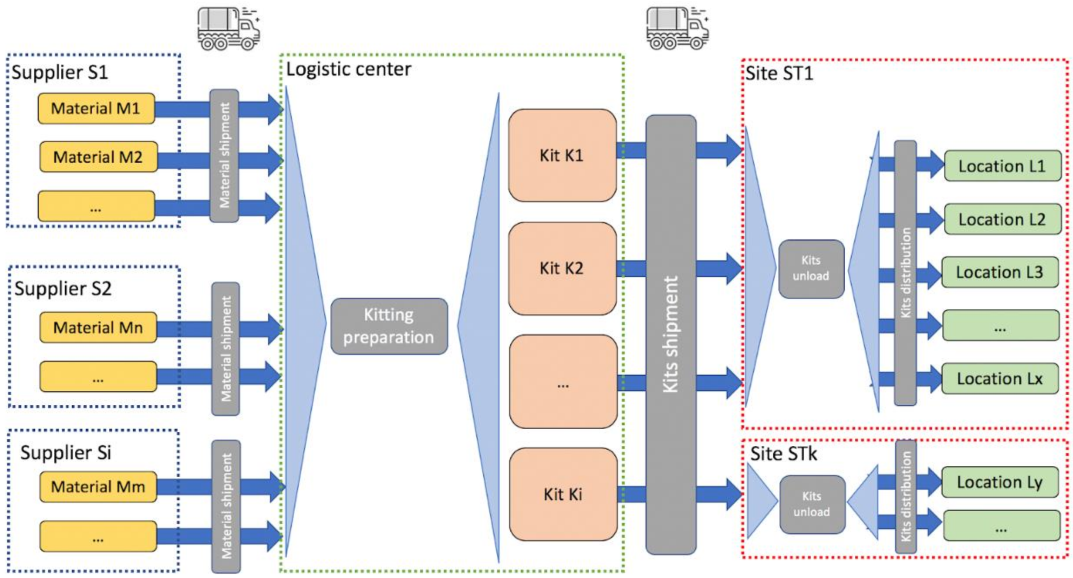


Fig.1 The kitting logistics process (Zheng et al. 2020)

At the designated time, typically around one day before the corresponding task will start, the kits will be delivered to the site. This delivery time is determined by the progress of the construction, which also applies a Just-In-Time (JIT) delivery method for the following operations on the site. When the kits are delivered to the site, they will be unloaded and distributed to the required locations for corresponding tasks. Kitting increases work productivity and workflow stability as it reduces logistic work of professional workers and enforces workers to follow the planned schedule and restrict workers moving to another work location. It also decreases interruptions and material waste. It can also enable pre-assembly of components and materials in the logistics center, further improving work productivity (Tetik et al. 2018).

To work properly, kitting sets some requirements for information management and its digitalization. Figure 2 presents major elements of the kitting management system and their interrelations. First, digital design of the building, including its elements and spaces, should be utilized when defining bill of materials (BoM) for different tasks in each location. This requires that commercial products which have been purchased by general or trade contractor, should be linked to the elements of the digital building model. This element- and space-based BoM information combined with the digital planning information about element- and space-linked tasks would enable defining assembly kits with specific bill of materials, their schedule and location. Regarding location information, three space elements are important: a) space into which the kitted material will be installed, b) workspace which 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.

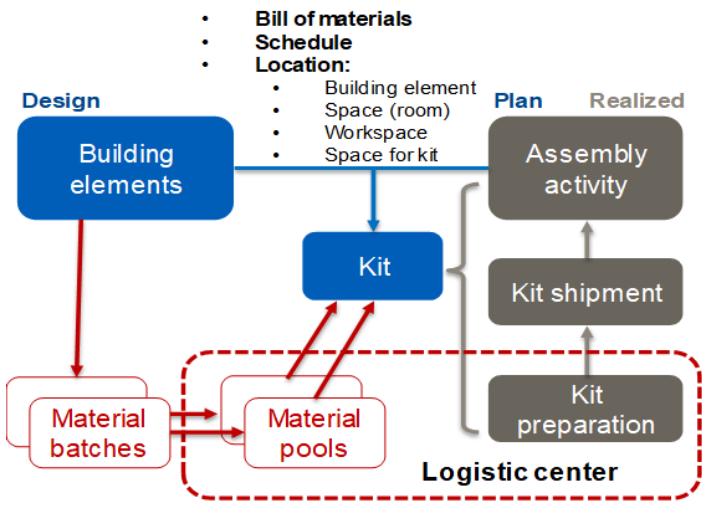


Fig.2 Requirements for digitalization: the kitting logistics process

From material point of view, it is important to enable digital management of logistic center'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 center. 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.

## 5.3. Collaborative planning

The centralized top-down management and production control currently used in construction are not perfectly serving the industry needs in nowadays complex multi-player construction workflow. General contractors do not have the skills, knowledge, and resources needed to plan the production actions of subcontractors on a detailed level. Obviously, the centralized top-down model is also one of the main reasons for the construction industry's production phase productivity issues. The best knowledge of concrete construction actions is with the people and organizations who are doing the work in practice. By involving these people, subcontractors, and teams, in the planning and coordination of their own day-to-day tasks, the problems of the construction implementation phase could be reduced and construction productivity improved. Switching from a centralized top-down method to a federated and parallel collaborative planning model is not easy. If it would be it would be definitely done already by somebody. The change will require both technological and socio-economic changes which are getting closer as the digitalization transformation proceeds.

As described earlier in this document major steps have been taken with currently available technology to improve situational awareness. However, technology has focused so far mainly on creating a reactive situational picture. Information on the progress of work and processes is reasonably easy to gather through different technologies like point clouds, computer vision, sensors, and status services developed for monitoring. This information is very valuable as it provides the actual situation of the work. This truthful information about the current situation is one of the cornerstones of planning coming activities. In the future, the as-built information collected from the workflows will also play a key role in machine learning-based systems to be used to steer the processes.

The proactive part of the situation picture consists of planned future actions. This is where the collaborative planning steps into the situation picture. A shared understanding of the coordinated granular tasks is potentially one of the key ways to improve productivity in the construction phase. Once collaborative planning is applied, in all likelihood, a significant part of quality problems caused by construction defects will also be solved. However, collaborative data-driven planning has not been feasible so far due to the technological and socio-economic reasons described above in this document as well.

As previously described, point applications focusing on solving individual sub-problems have not created a technological platform to solve multi-actor collaborative planning and workflow. In an open market economy, it is very unlikely that all parties to all projects will switch to a single centralized application. Thus, different applications need to be able to integrate based on common data. A natural consequence of this is that systems must understand information and its meaning in the same way. The ontology development described earlier in this document plays a key role in this.

Detailed, granular, and intensive action planning requires intensive and granular information sharing. The long transaction that is an inevitable consequence of file-based technology makes the file-based technologies for sharing information in a dynamic environment helplessly unusable. Changes in the situation, for example in Takt Time Planning, must be able to be communicated in practice in near real-time. The same applies to changes in the resource situation, material deliveries and operating environment, etc. The tasks dependent on changes must be able to be updated basically in real-time to guarantee the flow of production in the event of a disruption.

Satisfying the prerequisites for dynamic integration is becoming achievable as a result of the latest technological development. Applications must be able to provide up-to-date, consistent information on planned tasks. The obvious scenario for solving this is a federated data management model where different applications are in real-time connected to data services sharing the agnostic standard workflow data. Applications have always the same information and content available, allowing applications from different vendors to work seamlessly together. The transformation between the application data model and the shared workflow data models are the responsibility of the application (in the same manner as BIM solution are transferring their native formats to sharable IFC format). This, of course, requires standardization. Different systems need to have a common understanding of the concepts and meaning of the data. The development, application, and standardization of ontologies play a key role in this part of the development.

When technology allows systems to work seamlessly and intensively together, the socio-economic problems mentioned earlier in this document remain. A cloud-based federated system will be able to share the situation, plans, and changes objectively and quickly. The potential organizational resistance against transparency can slow down the progress as described in earlier sections. Resistance is also likely to arise on the individual level when new technology is introduced. For collaborative production planning to work, individuals need to be involved in the process on a large scale. This places significant demands on the usability of applications. Technology needs to be easy to use and intuitive to deploy. Besides, every user must experience that they receive more than they give. Value-added experiences can be divided into two different categories. Users need to experience that applications are facilitating their work by bringing them information or services that immediately help their normal daily work. Also, the use of technology expectedly results in a reduction in process disruptions and an overall improvement in the process, which indirectly improves the operational capabilities of employees. The first one keeps the guard down and allows the spreading of digital tools. The latter is probably the fuel for the process change towards collaborative planning. People feel that technology and a collaborative open action model will help them and start the process of change that technology enables. The win-win scenario gradually gains ground and the behavior of people – the process – starts to change.

Steve Jobs has reportedly stated: "Technology Doesn't Change the World, People Do". Some pieces of the technology (ontologies, services, interfaces ...) for collaborative planning have been developed in the DiCtion project. The development continues in various quarters. Bits and pieces of next-generation tools are released in different systems and applications. With these tools, people can already start to transform towards openness and collaboration.

## 5.4. Digital Workflows for supply chain management

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

Digital workflows would enable all project parties to know the up-to-date status of the construction site and better forecast into the future activities (Figure 3). For example, a better situation picture would allow understanding whether is there a need to adjust plans due to actualized deviations.

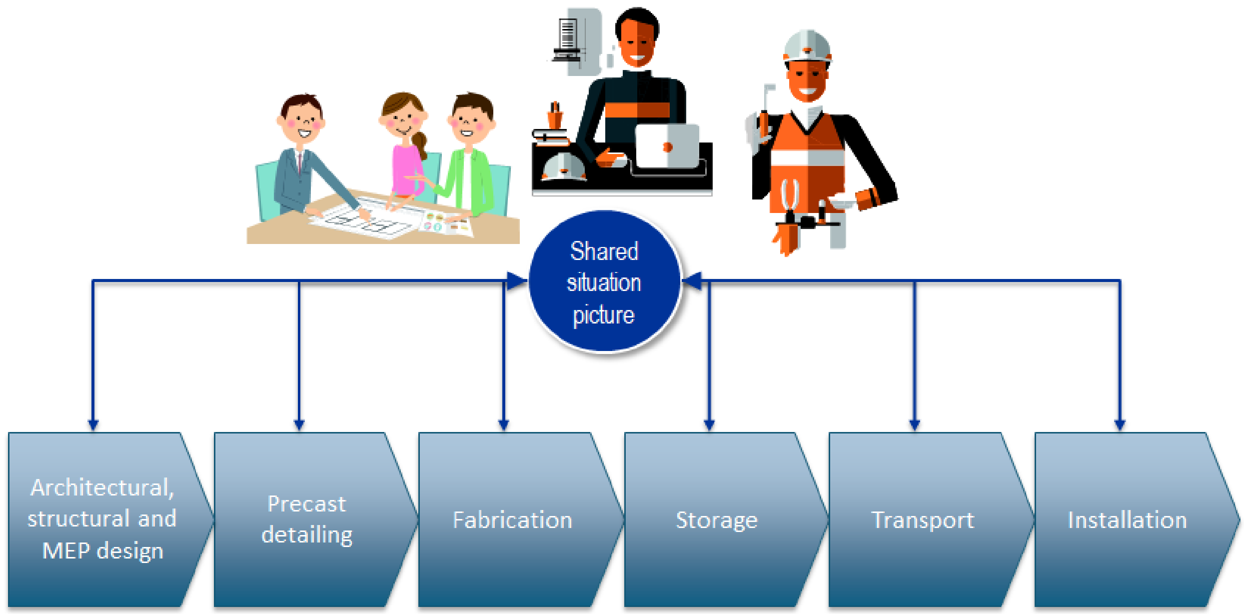


Figure 3. Shared situation picture allows better forecasting.

Our study reports seven use cases, including the needed inter-company data flows, to support efficient supply chain management of prefabricated structural elements (Lavikka et al., 2021). These use cases are the following (Figure 4):

**1. Optimization of the schedule of designing and producing elements**

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

**2. Optimization of the look-ahead planning**

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

**3. Planning of the shipment of elements in transportation**

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

**4. Delivery capacity confirmation**

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

### 5. Planning of subsequent shipments

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

### 6. Standardised transportation management

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

### 7. Issue management

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

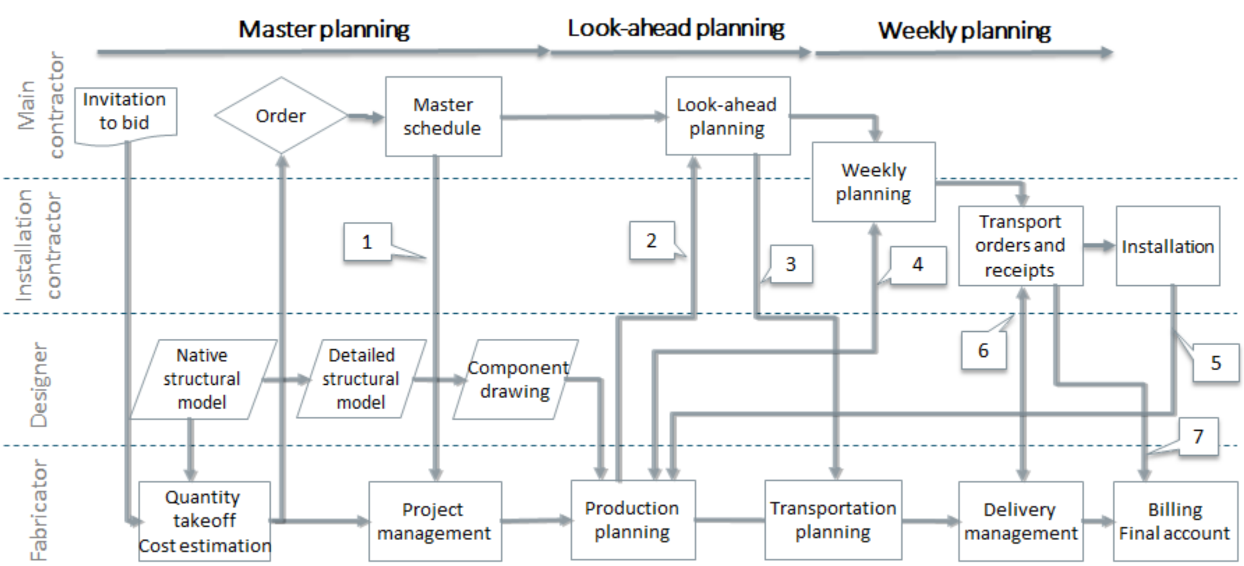


Figure 4. Digital dataflows of the seven use cases. (adopted from Lavikka et al. 2021)

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 optimizing productivity in the form of reduced costs and duration and improved construction worker safety on-site. Also, 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. Call for action

The shift from current Construction 1.0 to Construction 2.0 is systemic and requires simultaneous changes by many actors in the supply chain. The DiCtion consortium of companies has started the change in their own organizations and supply chains. All companies in the consortium have taken significant steps to digitalize their operations and solve both technical and business prerequisites of digitalization. However, most of the players in the market are not moving yet. We need standards and most of the industry to move in the same direction to achieve critical mass. In Finland, we currently have good momentum and we are looking forward to sharing ideas with other construction industries worldwide.

We call on all readers of this document to take actions in your local industry and in your own company. Join us in changing the culture of construction to collaborative, trustworthy and transparent so that digitalization can happen. Adopt interoperable solutions based on common understanding of digital workflows. Do not fall victim to large players who try to sell one solution to solve all problems but require interoperability from your vendors. Implement standards, such as GS1 for construction products. Together, we can change the way world builds and move construction to digital age!

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