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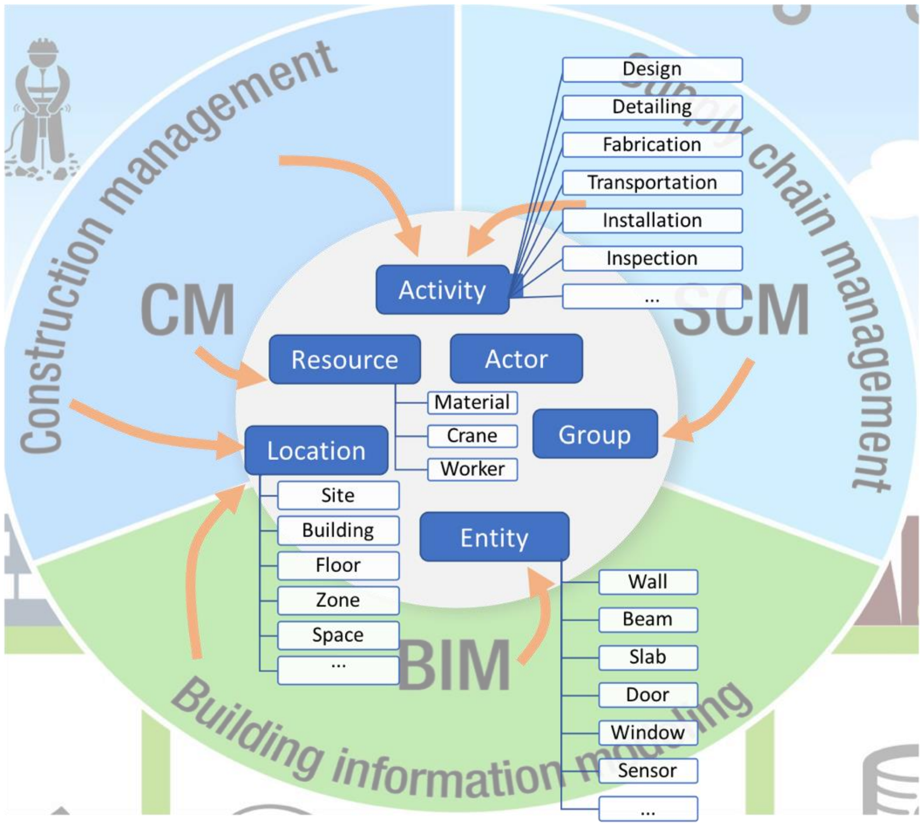

DiCtion: Deliverable report for Work Packages B and C

Prof. Olli Seppänen

Dr. Seppo Törmä

Doctoral students Yuan Zheng, Joonas Lehtovaara

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Introduction

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 are 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.

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. 2012). 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.

On social and collaborative side, we decided to start from the point of view of takt planning (e.g. Haghsheno et al. 2016, Frandson et al. 2013) because it 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). 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 distributed takt model 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.

The document is structured as follows. First, we explain our findings related to current state of planning based on social network analysis. Then, we present the data model of collaborative planning which incorporates space planning into the DiCtion ontology. Third, we outline the distributed planning process utilizing the ontology. Finally, we describe future research that should be carried out.

Social network analysis to understand requirements

In order to understand the requirements for collaborative workflows, we set out to answer the following research questions:

1. *Which kind of patterns of communication and decision-making emerge within the production?*
2. *How production participants, especially heads of trades and workers, perceive the planning and control of work?*

To answer these research questions, a survey-based social network analysis (SNA) with a single case (construction project) and multiple sub-cases (work tasks) was chosen as a primary research method. The inspected case was a commercial renovation project located in Espoo, Finland, and the inspected tasks were i) electrical work, ii) VAC works, iii) locking, and iv) painting. SNA was chosen as a method as it is exceptionally well suited for analyzing complex project networks' communication and decision-making patterns objectively (Lee et al. 2018). Project documentation, one structured interview, and 24 survey answers were used to determine the social network of the project of the determined work tasks. In addition, to validate the findings of SNA and deepen the understanding regarding the second research question, four semi-structured interviews of heads of trades and workers were conducted, which covered the inspected work phases, respectively.

Results

The results were analyzed from two viewpoints, holistic and egocentric. First, a holistic analysis of the whole production's communication channels was carried out. Second, networks of the decision-making patterns and channels regarding the work tasks were analyzed individually. Results are illustrated with 'Gephi' software (figures 1 - 5), presented below.

The overall communication network (figure 1)

It was found that the superintendents are the most vital links of information exchange during the production. The superintendents distribute general information between the work tasks and seem to possess the most up-to-date situational awareness of the current progress of the production. Even though the superintendents were not the most active decision-makers, the information regarding different decisions was passed through the superintendents. Some two-way communication happened without the superintendent being the direct link (such as between trade heads and designers), but it was validated on the interviews that the information almost immediately reached the responsible superintendent.

The traditional hierarchical structure of operations was demonstrated in the communication between the head and workers. Whereas communication between superintendents and heads was mainly two-way, between heads and workers, the communication was mostly from head to worker. On the other hand, the interviews indicated that it might not mean that the workers are only following top-down orders, but that the workers require a vast amount of information from the head and superintendents to be able to perform and plan their daily work.

Face to face communication was by far the most used means for communication, especially between the site personnel, followed by communication by phone. Meetings and email were also identified as crucial channels, especially amongst the managers and designers.

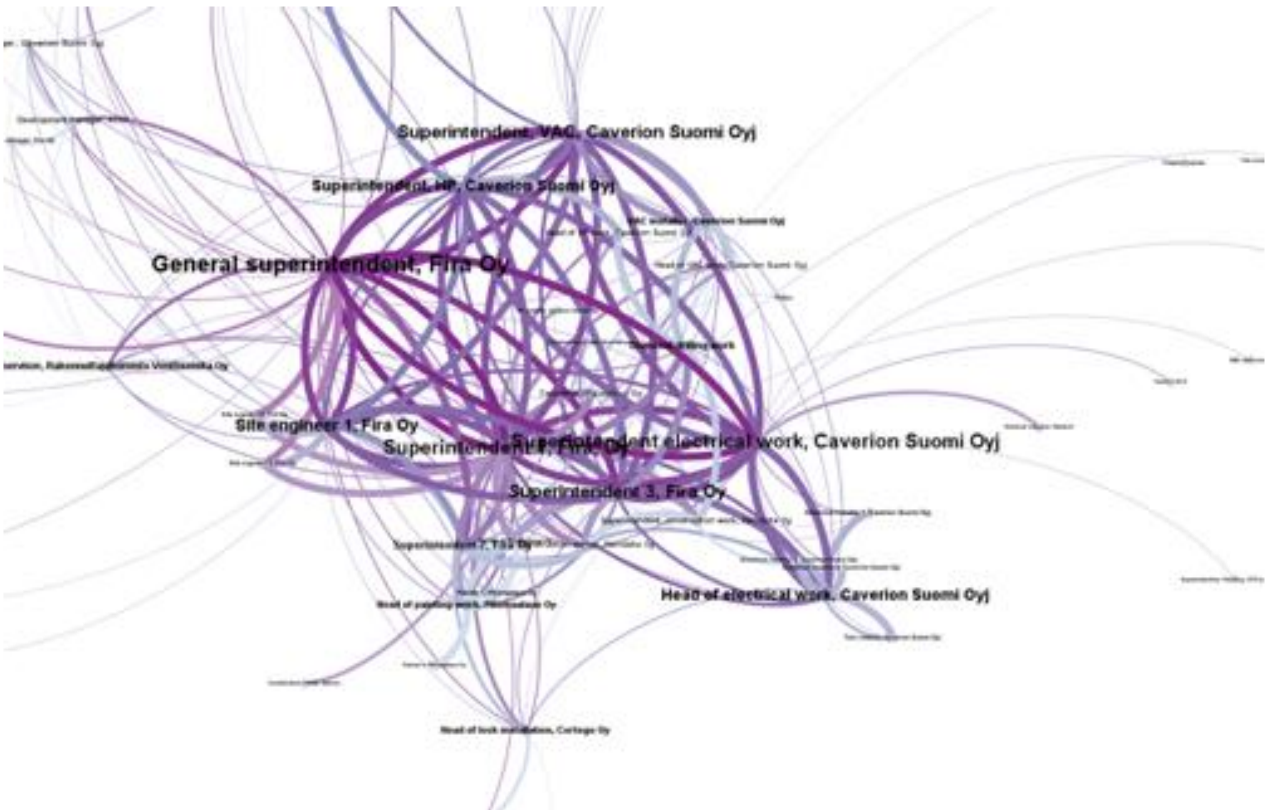


Figure 1: The overall communication network

<u>Task specific decision-making networks (figure 2a, 2b, 2c, 2d)</u>

The mapped decision-making networks revealed that even though information flow happens through superintendents, heads and workers play a vital role in the decision-making process during the production. In electrical works (figure 2a), most of the decisions were made between the head of electrical work, electrical work superintendent, and installers. In VAC works (figure 2b), most of the decisions were made between the VAC and heating & plumbing superintendents as well as installers. In locking (figure 2c), decisions and planning went primarily through the head of the lock installation, who also worked as an installer. In the painting (figure 2d), decisions and planning went through the head of painting work, who also worked as a painter.

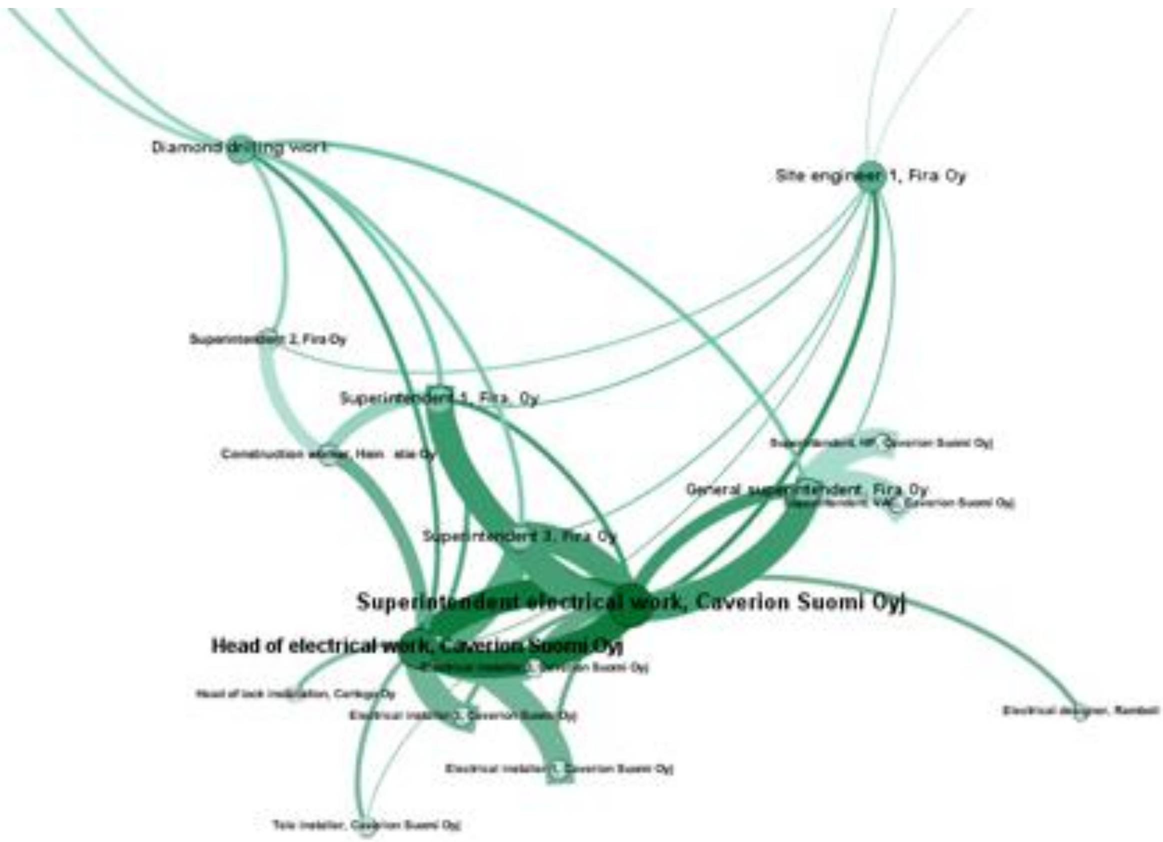


Figure 2a: Electrical works

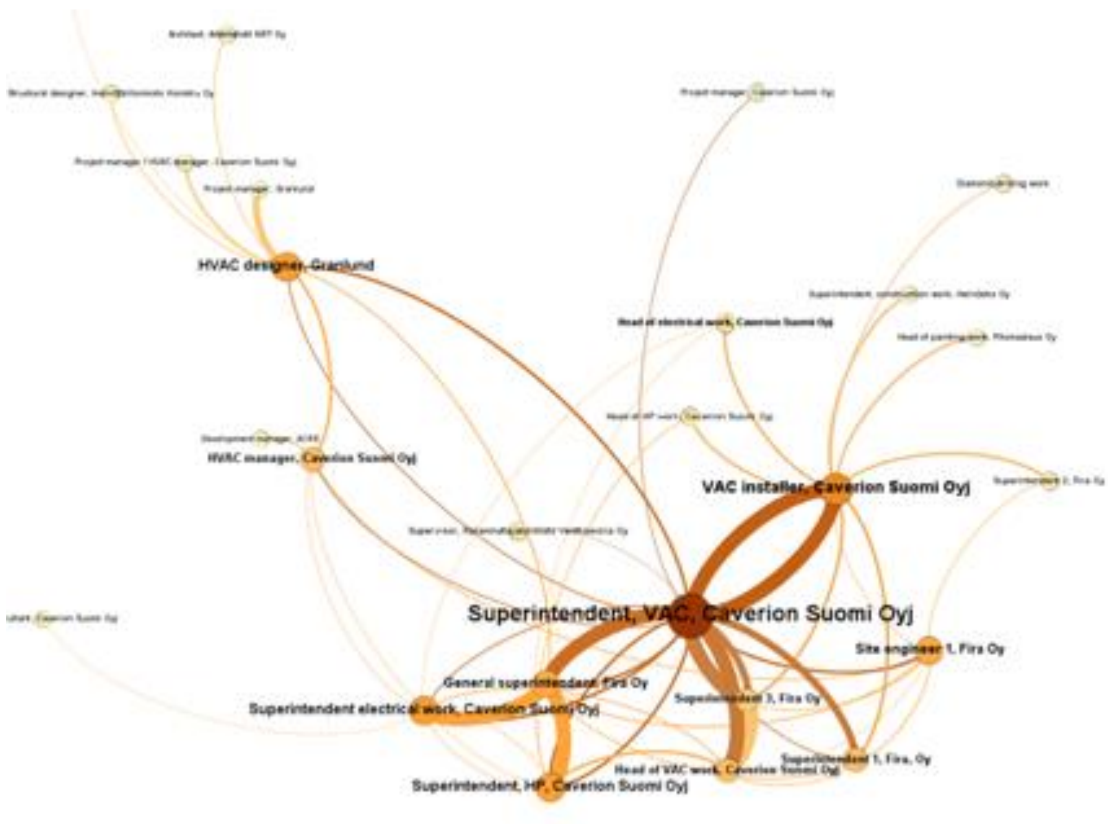


Figure 2b: VAc works

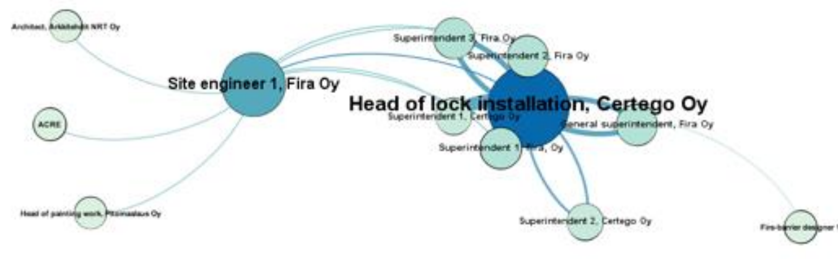


Figure 2c: Locking

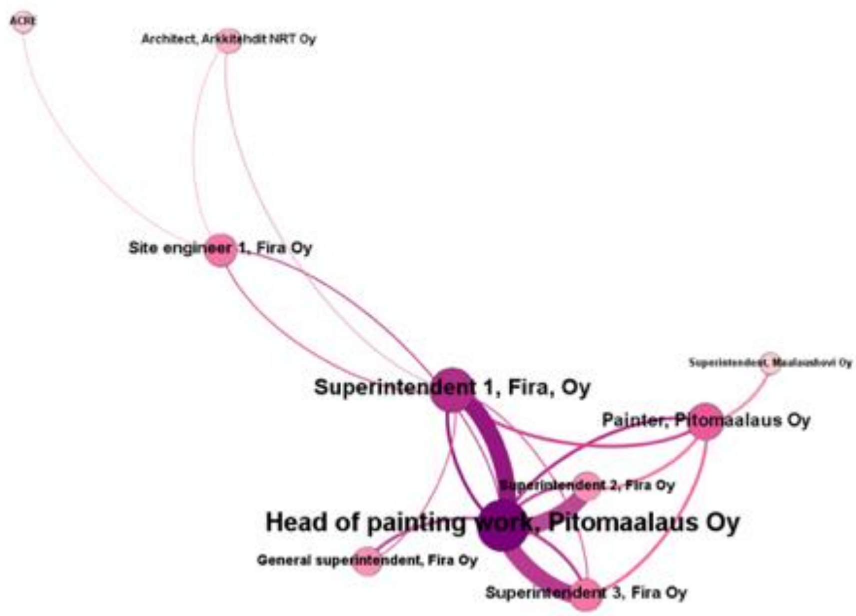


Figure 2d: Painting workds

The role of the superintendent in the decision making was related on how actively the superintendent visited the site. Otherwise, the heads of trades were in control of most of the decisions regarding operations. In addition, it was pointed out in the interviews that heads generally give workers flexibility to plan their own tasks in given frames most of the time.

It was also noted that the heads and workers were not frustrated with their role in planning operations, but quite contrary, seemed to feel that the increasing amount of planning is a sign of a well-working and collaborative production process.

Head of painting/painter:

”I make most of the decisions regarding planning and control on the site…

I feel that I can contribute as much as I want.”

Head of electrical work/installer:

”We will create the schedule for every one to three weeks in collaboration with the installers and superintendent. …

Lock installer:

”Well, in fact, nobody does the planning for me. I will make it in the run and apply as needed. … So, I make all of the decisions regarding the workflow.”

VAC superintendent:

”Head of VAC and the installers, they are the best experts on planning the work …

they also have the best insight on what has been done …

the VAC superintendent has the most recent information regarding the situation.”

It was found from the network analysis and the interviews, that the role of heads regarding design management and finalizing the designs for constructability was quite significant. For example, the VAC superintendent was managing the detailed design running during the production, thus increasing his role significantly in decision-making. For heads and workers to perform work planning effectively, designers and superintendents were found to hold (or at least distribute) the most critical information. It was noted that efficient communication, especially between heads and designers, as well as between heads and superintendents, was essential for effective work planning and control. This was especially noted in electricity, and VAC works.

Head of electrical work/installer:

”The designer does not develop the designs for the level of detail that is needed on the site …

in lots of cases, we make suggestions for the designer, and he approves them.”

Head of painting/painter:

”We don't have any specific designs beforehand.

We make decisions as the tenant tells us what he/she wants.”

Discussion

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, heads and workers still tend to plan their work regardless of the master plan implemented, 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 subcontractor heads 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 finished to serve the accuracy needed for installation, and the heads were often in charge of the final steps in the design management process.

The social network analysis revealed that project participants from all levels of hierarchy believed to make important decisions on planning their work and that people generally wanted to be involved in the planning process. The notion indicates that the heads 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 of the project enabled the 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 3)

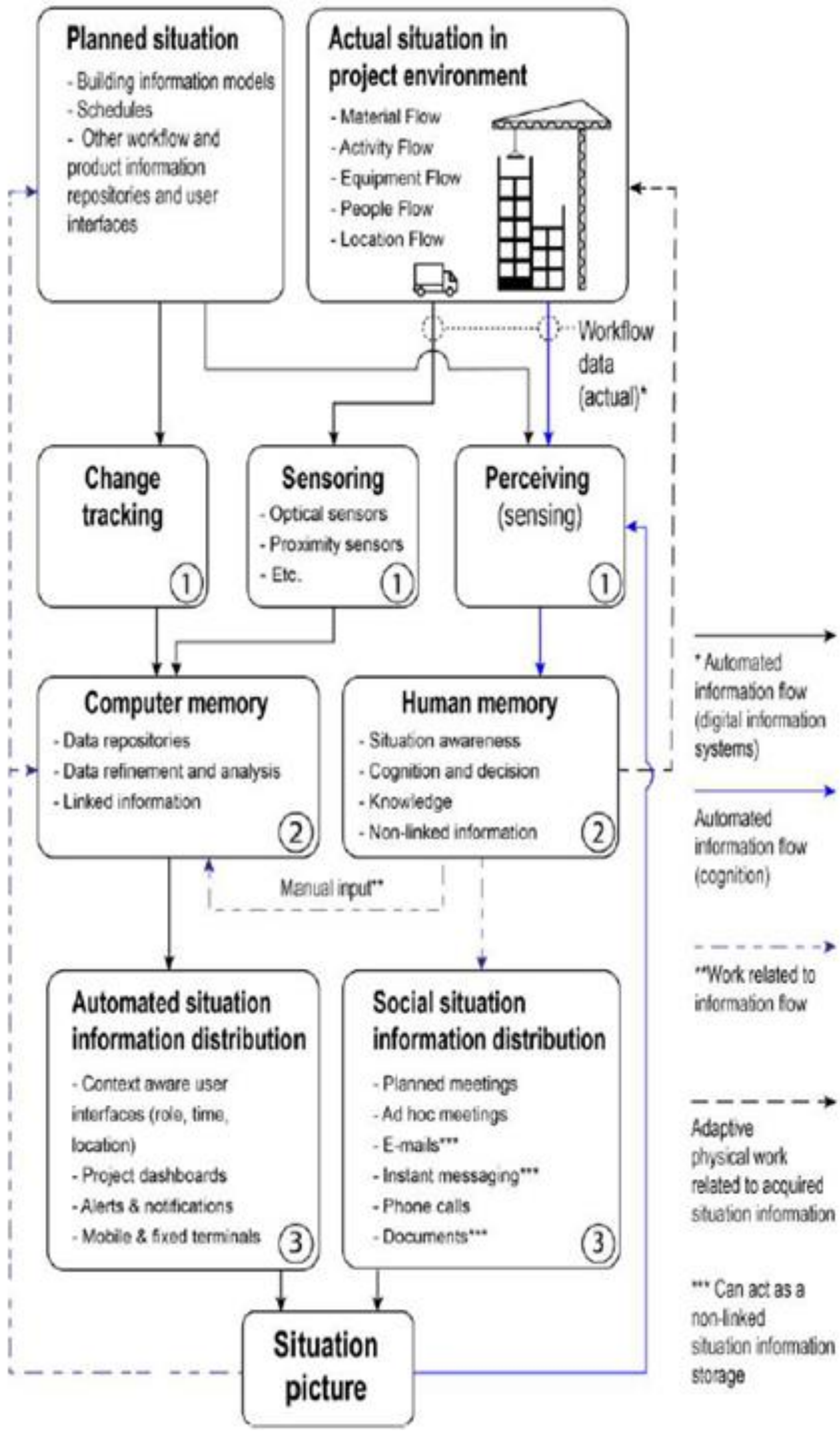


Figure 3: Situational awareness in construction (Kärkkäinen et al. 2019)

Common generic workflow model

Introduction

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.

At a more concrete level, the theoretical framework is lean construction that provides the underlying model of construction flows and their relations with activities. The concrete goal is to develop the Diction ontology (1) to include a representation for different kinds of flows and their relations with activities, and (2) to represent the sequencing constraints derived from the flows in the ontology. Sequencing constraints are temporal constraints between activities that can, for example, state that one activity must precede another or that two activities cannot be in execution simultaneously.

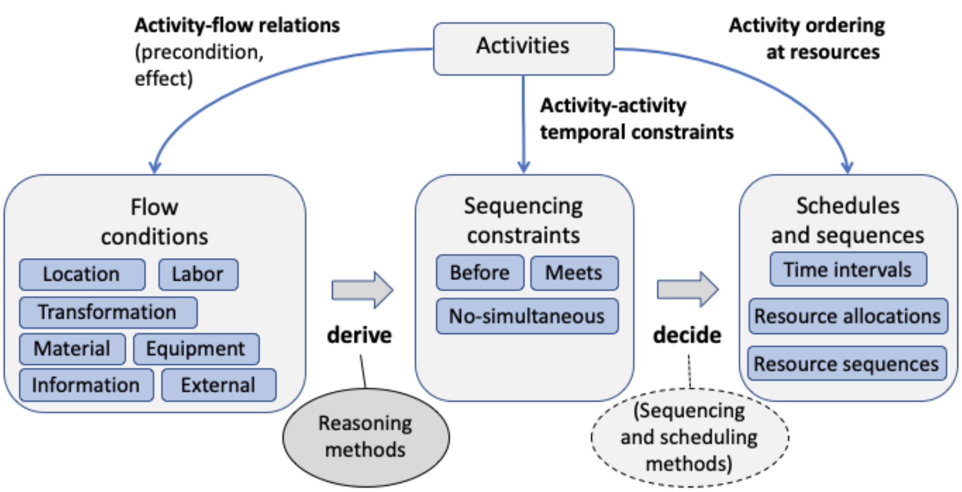


Figure 4 - From flows to sequencing constraints to sequences

Sequencing constraints can leave a lot of freedom for the order of operations at different resources. Which sequence is better than another depends on context-specific factors and preferences. The final operation sequences can be created either by manual or algorithmic methods (Figure 4) considering the constraints and preferences. If a sequencing method does not take all the constraints into account, it can still be checked afterwards whether the produced sequences satisfy those constraints. It should be mentioned that this data model focuses on the derivation of sequencing constraints and the representation of the sequences, but not on the methods to generate final sequences - although some examples of them may be given.

In this section, we will discuss the nature of activity-flow relations and temporal constraints, and how to derive the latter from the previous. The ontology definitions of the necessary relations and constraints are essential, since the objective is to be able to process the sequencing information in automated, machine-to-machine manner. An additional objective is the maintenance of the provenance of the information: for instance, which flow relations are the reasons for a temporal constraint. These relations can be used to reflect the sensor or status data related to flow objects to the schedules for automated progress updating.

Activity-entity relations

Lean construction (Koskela, 1999, 2000) has borrowed the concept of a flow from the domain of lean manufacturing. In lean manufacturing, a flow refers to the entities to be transformed (materials and components) moving through stationary production resources. The primary goal is to keep components in movement from task to task in a proper order and without interruptions, and secondarily on smooth sequences of tasks on different resources. The repetitive and stationary nature of manufacturing makes it possible to focus on improving the flow velocity and on the simplification of flows: in a factory setting there is a static background of resources in front of which the flows of components and materials form the dynamic foreground.

The concept of a flow can be applied also in construction, but it is not as natural or apparent as in manufacturing, since the background and foreground get mixed. Some resource-like entities are stationary (such as spaces) whereas others are non-stationary (labor, equipment, trucks). Likewise, some product-like entities are non-stationary (components and materials) while others are stationary (spaces). And as can be noticed, the spaces within a building can simultaneously be considered as resources of some activities - interpreted as workspaces - and the products of other activities; indeed, the creation of protected spaces can be regarded as the ultimately goal of construction.

Moreover, there is much less repetition in construction and therefore the flows do not form identifiable and visible "rivers" but rather networks of small creeks spreading around. Still, if events faced by one object - a component, material lot, resource, or location - are studied from the perspective of what are the other objects it faces, it is possible to see other objects flowing towards it: movable resources (labor, equipment) see the arrival of different spaces, materials and equipment, the labor resources see an arriving flow of information objects, and so on. In that sense, flow modeling is a valid way of regarding the interactions and dynamics in construction, even though the overall pattern of flows is different from that of manufacturing.

Flows and conditions

Flows related to construction activities are classified in different categories. The exact categories depend from source to source; the following are by Koskela (1999, 2000):

1. *Precedence*
2. *Material*
3. *Labor*
4. *Equipment*
5. *Workspace*
6. *Information*
7. *External*

The categories are illustrative of the variety of ingredients of activities. They can be used as reminders in the analysis of activity dependencies, to ensure that all different types of flows are covered. However, the exact categories are less important for the management of the flows, since from that perspective it is crucial to know all the specific flows related to activities. It should be noted that each activity can have several flows belonging to some of these categories and not necessarily any flows in some categories. For example, precast installation requires two labor flows (a crane operator and an installation crew), while drying activities do not need labor at all. Moreover, movement activities do not need specific workspaces, and some indoor activities are not sensitive to external conditions.

Different flows come from different sources, primarily from information related to end product and resources (Figure 5). 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. Figure 5 shows a set of flows encountered by activity A1, together with the preconditions, execution conditions, and effects of activities. In the figure the essential flow concerns a component that is transformed by the activity and whose status changes as a result; this would belong to the category of precedence flows.

It is worth stressing that even though the ontology allows the representation of many different kinds of flows, each construction project can naturally consider and decide completely freely which flows it is able and willing to model and monitor. If it is not possible to identify or monitor some flows, they can just be left out. There are possible conflicts that might arise during the execution time since some of the important flows have been ignored during the planning time. If that should happen, the conflicts can be solved as part of normal everyday construction management work on site. The flow model does not force a project into some kind of straitjacket; it just provides an opportunity for more detailed advanced planning and incorporation of sensor based monitoring information into models. All the existing construction management tools can methods can still be utilized as well.

Effect-precondition dependency

In order to execute A1 (Figure 5), some of the flows must satisfy a set of preconditions. The component that is the focus of the activity - such as a wall to paint or a window to install - has to be in the correct status. For instance, a wall needs to be in a status “taped and finished” before painting can begin, or a window has to be completely manufactured before installation is possible.

A major type of preconditions related to all physical ingredients of an activity - components, materials, equipment and labor - is that they must be located at the place where the activity is executed. There are additional preconditions that the relevant information (drawings, specifications, installation instructions) has to be accessible to the labor of the activity. Nowadays, the information is increasingly delivered through digital channels, which means that the paper prints do not have to be physically located at the workspace. Rather, accessibility can mean that the labor has mobile devices, that the specific information has been produced, and that the labor has access rights to the information (for instance, in a BIM collaboration system or a document management system). Finally, some activities have preconditions that refer to external, environmental factors such as proper temperature or humidity levels.

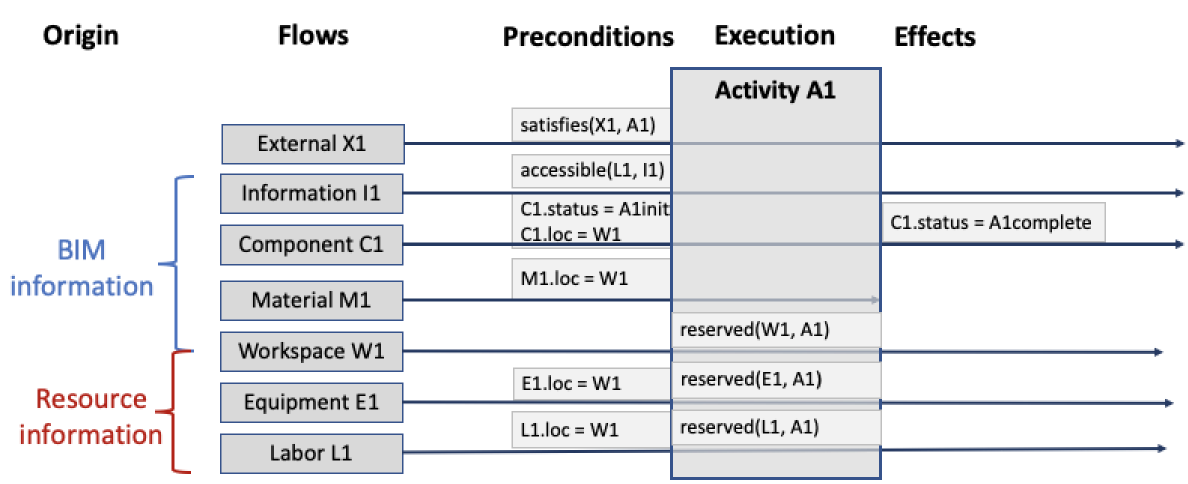


Figure 5- Flows and activities

The counterpart of preconditions are the effects of an activity. They come in two variants:

- Add effects: what new conditions will be in effect after the activity;
- Remove effects: what preconditions do not hold anymore after an activity.

In the example of Figure 5, there is one add effect: the change of the transformation status of the component C1. Activity A1 is thus a way to transform the component C1 from status A1init to A1complete. The value adding activities can all be represented as such transformations. For example:

- painting is an activity to transform a wall from status "tape and finished" to status "painted";
- transportation transforms the location of a shipment from one location to another;
- installation of a component (e.g., window w1) to its base element (e.g., a wall a1) transforms object from unattached to attached to the base (e.g., w1 attachedTo a1).

The chaining of transformations creates sequences of activities. For instance, consider a component w1 of the type wall. Since there are activities:

- hanging drywall: precondition is the status frameConstructed, effect is to add the status drywalled,
- taping and finishing: precondition is the status drywalled, effect is to add the status taped and finished,
- painting: precondition is the status taped and finished, effect is to add the status painted, and
- skirting: precondition is the status painted, effect is to add the status skirted.

When these preconditions and effects of different activities are considered and matched with each other, the only resulting workflow of the activities is

- Hanging drywall – taping and finishing - painting - skirting

Thus, when one activity has an effect that another one requires, it creates a dependency between the activities. Sometimes, as in the example above, these relations result in a fixed sequence of activities. Often, however, the transformations underspecify the sequences. That is, a lot of flexibility may be left for the order of activities.

Competing resource needs

Construction - like all human activity - is constrained by limited resources. There are typically numerous activities that require the same resources - a crane, a painter, a workspace, a drill, a truck - that are reserved by an activity for the period of its execution and can be reused later by other activities. The activities are thus competing for the use of the same resources.

The resource type flows - labor, equipment and workspace - are reserved for the duration of the activity execution and released after that for other activities. Since many different activities may need to reserve the same type of resources - such as all painting activities require painters, or all activities at the same wall (framing, hanging drywall, taping and finishing, painting, skirting) need overlapping workspaces - the available resource capacity limits the number of such activities that can be in execution simultaneously. This creates temporal constraints between activities.

If temporal constraints are not identified, they need to be handled during on-site construction management activities. There will be conflicts if activities want to use more of a resource type than what is its available capacity. That kind of conflicts cannot be completely avoided, but their frequency can be reduced and they can be anticipated earlier if different resource requirements are properly modeled.

Activities on groups

A ubiquitous phenomenon in construction planning are activities that are performed on groups of entities (or flows), instead of single entities. For instance, fabrication is often done as production lots or batches, components and materials are transported to a construction site as shipments, not as individual entities, ingredients of an on-site activity (components, materials, equipment, documents) can be packed as kits that are moved to the workspace as a whole, purchasing is done as procurement packages, and so on.

It should be stressed that these activities are indeed single activities whose focus is a complete group. As illustrated in Figure 6, they are not aggregations of lower level activities for each member of the group. The essential challenge in modeling them is to capture the packing and unpacking activities of groups and the status changes that the group level activities cause for the members of the groups.

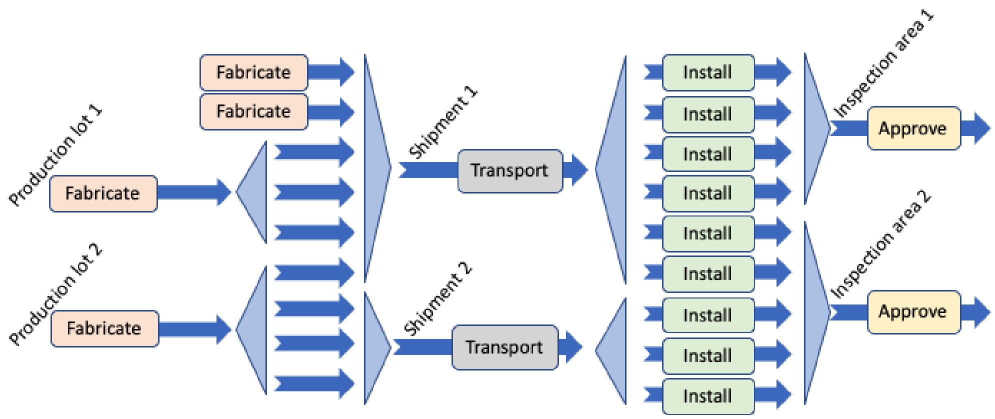


Figure 6 - Grouping and ungrouping of flows

Workspace overlaps

Space - as noted above - has a dual role of being both a part of the end product being constructed and the resource of many of those physical construction activities required to complete the end product. In the latter sense, the space can be considered as workspace. As a resource workspace is more complex to represent and manage than other types of resources, such as labor or equipment. To enable distributed planning, a more flexible use of working space in bottom-up planning was identified as a major requirement for DiCtion ontology.

Workspace concepts

To get into the details of these complexities, the treatment below is adopted from Akinci et al (2002) that propose a 4D-SpaceGen ontology for representing workspaces in a generic manner for different types of activities and deriving automatically the concrete workspaces of activity instances as 3D bounding boxes.

4D-SpaceGen ontology considers four different kinds of workspaces that can be associated with an activity:

- occupied spaces
    - labor crew space: the space where the crew is working;
    - equipment space: the space occupied by equipment such as a lift;
- non-occupied spaces
    - hazard space: the space threatened by the activity (by falling objects, fumes, sparks);
    - protected space: the space that needs to be kept safe from particular hazards.

An important thing to note is that the workspace requirements of an activity depend on the construction method used. For instance, workspaces - including labor crew space, equipment space and hazard space - are different if windows are installed from inside or from outside, and in the latter case, whether a scissor lift, swing stage or scaffolding is used.

The properties of the generic workspace requirements in 4D-SpaceGen ontology are the following:

- *Reference object*: in relation to which the space is located
- *Orientation*: where the space is with respect to its reference object
    - The values come from a limited vocabulary:
        - above
        - below
        - outside
        - inside
        - around the connected side
        - around
- *Volumetric parameters*: the size of the space (length, width, height)
    - values of the dimensions can be
        - constants (e.g., 3 meters)
        - computed from the reference object (e.g., the width of a wall)
        - max value possible (e.g, height from the ground up to the labor crew space)

This set of properties is, however, insufficient to correctly specify the positions of many indoor activities. Consider, for instance, painting of an indoor wall. If the wall is the reference object, how can the orientation values define which side of a wall is to be painted? One possibility is to add an additional property to workspaces, which is the *reference location*. The reference object must be either inside or at the boundary of a reference location. The workspace location is then at the orientation with respect to reference object, when viewed from the reference location. For instance, the labor crew space of wall painting is at the inside of a wall when viewed from the space.

In the following work packages, there is an interest in DiCtion to learn or adjust the workspaces from sensor information. One possibility are the heat maps of the labor crew based on indoor positioning data. This is likely to impact mostly the volumetric parameters, although the orientation could also be affected. The most immediate use for heat maps is to provide more accurate constant values of volumetric parameters.

One weakness in the 4D-SpaceGen ontology is in the orientation vocabulary. It is difficult to see how the orientation of taping and finishing, painting or skirting of drywall can be specified. The values proposed in the ontology are relevant to the sides of exterior walls (inside or outside); however, these do not apply to drywalls that have two insides and no outside. In the specific example of drywalls, there could be additional information about the space at the proper side of a wall. That is, instead of one reference object (the wall) there should be another reference object (the space) to define the orientation. The exact formulation of this in the ontology requires closer study.

Sequencing impacts of workspace requirements

The *spatial overlaps* of the workspace requirements of two activities can be used to derive constraints on the *temporal overlaps* of the activities. The rule would be as follows:

Two activities (a1, a2) cannot be in execution simultaneously (no temporal overlap) if

1. the occupied spaces of a1 spatially overlap with any of the workspaces of a2, or
2. the protected space of a1 that needs to be guarded against a particular hazard h1 spatially overlaps with a h1-producing hazard space of a2.

The process of using workspace information in DiCtion has the following outline:

1. Represent the **generic workspace requirements** for different types of activity
- reference object(s) with specified orientation and volumetric parameters
2. Derive the **concrete workspace requirements** of each activity from the generic workspace requirements using BIM models (or other geometrical frame of reference) of the building
- 3D bounding box (xmin, xmax, ymin, ymax, zmin, zmax)
3. Compute **spatial overlaps** between the concrete workspace requirements
- Computed as intersections of 3D bounding boxes
4. Create **temporal non-simultaneity constraints** between activities whose workspace bounding boxes intersect

An example of three tasks, each having a single labor crew space requirement is shown in Figure 4. The generic workspace requirements are represented in the semantic domain, the bounding boxes are at the spatial domain (shown in the figure in 2D), and the sequencing constraints between activities are in the temporal domain.

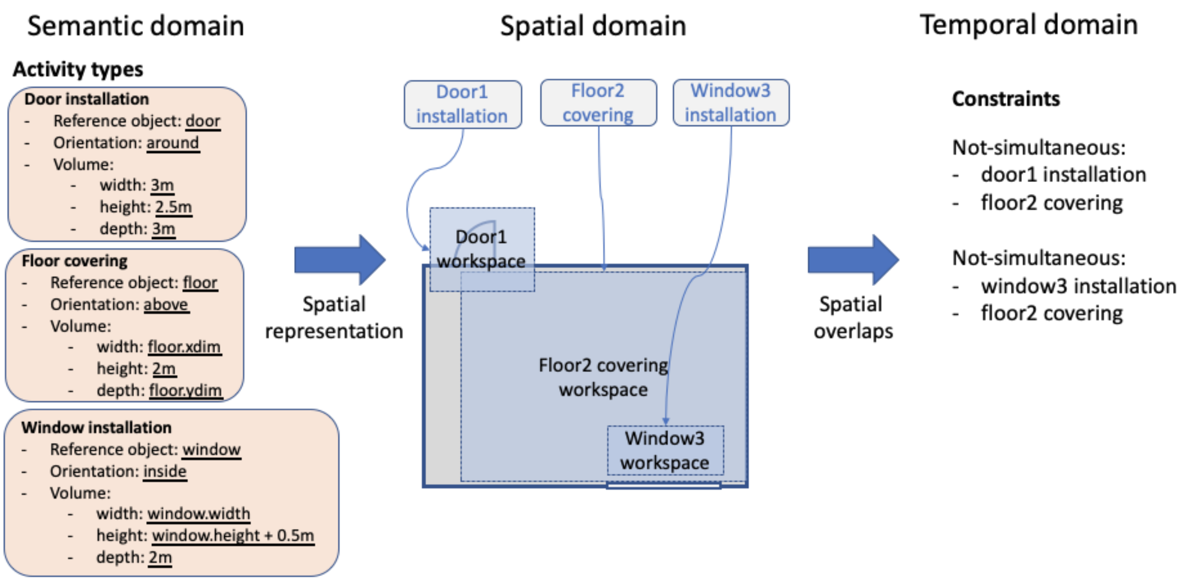


Figure 7 - From semantic workspace descriptions to spatial representation and temporal constraints

Workspaces and location breakdown structures

Workspace requirements are relevant in the later stages of construction planning when individual tasks have already been identified, based on detailed knowledge of components, groupings and work methods. In terms of the planning horizon, this concerns primarily weekly and/or lookahead planning. When takt planning and control is considered, the workspaces are considered in distributed work planning (micro planning), while a more uniform location breakdown structure is used in top-down planning of takt (norm planning).

In the earlier stages of planning - such as master planning or phase planning – detailed information about tasks and workspaces is typically not available yet. However, more coarse spatial information can still be used. In this phase, the spatial considerations are typically based on subdividing the volume of the site and buildings into sections, floors, zones, and spaces. They can also relate to site layout planning which defines the location of major construction site resources, unloading areas and storage spaces.

Location breakdown structures (LBS) (Kenley & Seppänen 2010) are hierarchical divisions of the space at the site to help in the planning of the activities and in estimation of quantities and amounts of work needed. The space is subdivided in different ways in each phase of construction, such as in frame construction or indoor construction. Consequently, multiple different LBSs can be needed during construction planning. For example, in LBMS and takt a different LBS is typically adopted for each construction phase.

Both the locations and workspaces can be modeled as 3D volumetric entities. Whether activities are associated with locations included in some LBS or if they have identified workspace requirements, these volumetric entities can all the same be studied for the possible spatial overlaps. As a general rule, if activities have spatial overlaps, they should not have temporal overlaps.

The hierarchical relations of locations in an LBS can still be important for automatic creation of constraints. Thus, for example the roof of the complete building must be on before any hanging of drywall should start anywhere in the building. This is a so-called layer 2 dependency in LBMS which would not be possible to achieve with overlapping workspace requirements because the roof does not physically interfere with drywalling. Layer 4 dependencies would be similarly difficult to cover with workspace requirements because they impact floors above or below for reasons such as gravity or support elements required to prop up formwork. Layered logic could be used to set up the constraints automatically.

However, if the purpose is to determine spatial overlaps and their sequencing impacts, locations and workspaces can be regarded as similar spatial entities. At the simplest level they can both be modeled as 3D bounding boxes; if a more accurate model is needed, more complex 3D volumetric representations such as prisms can be used. Additionally, individual elements could be assigned the locations. However, both locations and workspaces can be represented in a similar manner.

Temporal constraints

This section deals with the constraints between activities that relate to their mutual execution times. Temporal constraints are thus completely in the time domain and there are no references to the underlying flows or entities.

Temporal precedence of activities

The most important sequencing constraint is the precedence constraints that states that an activity needs to be executed before another. It can be defined either between intervals or time-points:

- time intervals
    - a1 before a2
- time points
    - a1.end ≤ a2.start

Precedence relations are transitive: if a1 before a2, and a2 before a3, then a1 before a3.

Maximum simultaneous activities

When two activities (a1, a2) require the use of the same resource, and if the capacity of a resources is one (that is, only one of the activities can use it simultaneously), then one of the activities need to be executed before the other:

- (a1 before a2) ∨ (a2 before a1)

This form of this constraint is a *logical disjunction*, and hence these are called *disjunctive temporal constraints*. If there are three activities (a1, a2, a3) that require the same resource, there is a need for disjunctive constraints between each pair of activities, to indicate that none of them can be in execution at the same time with another:

- (a1 before a2) ∨ (a2 before a1)
- (a1 before a3) ∨ (a3 before a1)
- (a2 before a3) ∨ (a3 before a2)

There will obviously be a problem with the proliferation of constraints when the number of competing activities grows. However, a more significant problem is that the above formulation of a disjunctive constraints is not expressive enough for many situations at construction sites. Often - perhaps even more often than not - activities require the same kind of resources but there are many instances of similar resource available. For instance, there can be multiple painters, multiple drills, and so on. A simple representation for the non-simultaneity constraints in the case where three activities require the same resource with capacity 2 is the following:

- max-simultaneous(2, {a1, a2, a3})

It states that in maximum 2 activities from the set of three activities {a1, a2, a3} can be in execution simultaneously. This can easily be generalized to any resource with capacity c, required by activities in a set A:

- max-simultaneous(c, A)

A minor extension could be to generalize this to variable resource requirements. For instance, assume that there are 2.3 units of capacity available, and activity a1 would require 1.8 units, a2 1.0 unit and a3 0.6 units. This could be represented by a constraint as follows:

- max-simultaneous-usage(2.3, {(a1, 1.8), (a2, 1.0), (a3, 0.6)})

However, it is not clear whether this kind of constraints are needed in practice.

As a final warning, it should be noted that disjunctions are problematic for optimization methods, since they tend to lead into a combinatorial explosion of alternative solutions. If there are *n* disjunctive constraints, there will be 2^n different alternative solutions to consider which is completely impossible except for very small problems (for instance, 100 disjunctions mean $2^{100} \approx 10^{30}$ alternatives). In practice, this means the following:

- Disjunctive constraints are problematic and should be avoided if possible. If there is additional domain information, sometimes they can be replaced with simple precedence constraints that are both stronger and easier to use by scheduling algorithms.

- When there are many disjunctive constraints, the optimization methods need to settle for solutions that can be computed efficiently but are likely to be suboptimal.

Other temporal constraints

Even though many scheduling algorithms are probably based on the type of precedence constraints and resource constraints as described above, there are situations where a broader set of temporal constraints can be needed.

An example is a casting activity c1 that is immediately followed by a drying activity d1. Since their flow requirements are different - for instance, d1 does not need the same labor, equipment or workspaces than c1 - they should be modeled as two separate activities. Now, it is necessary but not sufficient to say that the c1 before d1; in addition, there must be a constraint that d1 starts immediately when c1 ends (meets it at the end): c1 meets d1.

These kinds of relations have been defined in the Allen's interval algebra (Figure 4), which is also incorporated in the OWL-Time ontology (defined by W3C).

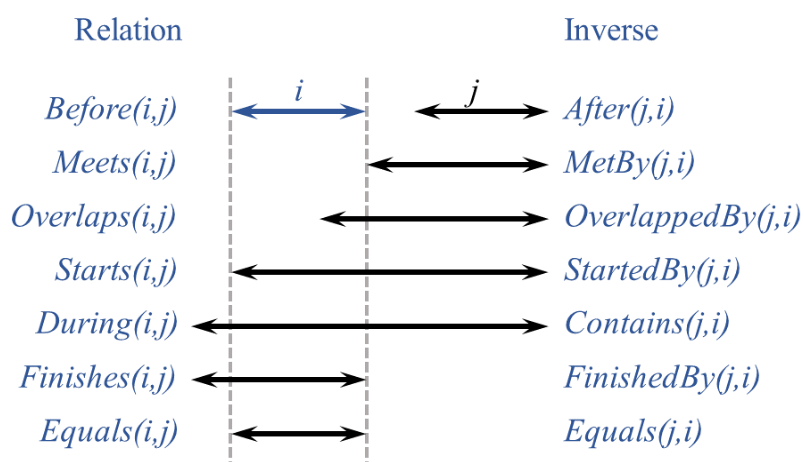


Figure 8 - Relations of time intervals in Allen's interval algebra

Some of these relations can be difficult for existing scheduling methods to utilize. The simple approach is just to ignore all unknown and settle with schedules that may result in some conflicts on construction site that then need to be managed using standard construction management practices.

Examples of activity definitions

In the following there are examples of activities and their relations to the states of different entities before (preconditions) and after (effects) the execution:

1. Transportation activity tr1 for a shipment sh1 from a location to another by truck tr1 operated by driver dr1

	Object	**Property**				
Activity	?tr: Transportation	from: Location to: Location				
Flows			**Preconditions**	**Hold conditions**	**Remove effects**	**Add effects**
Component	?sh: Shipment	loc: Location status: Status	locatedAt(?sh, ?tr.from) hasStatus(?sh1, Packed)		sh1.loc = tr1.from	sh1.loc = tr1.to
Equipment	?tk: Truck	loc: Location	locatedAt(?tk, ?tr.from)	reservedTo(?tk, ?tr)	tk1.loc = tr1.from	tk1.loc = tr1.to
Labor	?dr: Driver	loc: Location	locatedAt(?tk, ?tr.from)	reservedTo(?dr, ?tr)	tk1.loc = tr1.from	dr1.loc = tr1.to
Information	?wb: Waybill	loc: Location	accessibleTo(?wb, ?dr)		cn1.loc = tr1.from	cn1.loc = tr1.to
Workspace						
Material						
External						

2. Painting activity pt1 for a wl1 by painter pr1 using paint pa1 and requiring the workspace ws1

	Object	**Property**				
Activity	pt1: Painting	side: Orientation				
Flows			**Preconditions**	**Hold conditions**	**Remove effects**	**Add effects**
Component	wl1: Wall	status: Status	wl1.status = Smoothed			wl1.status = Painted
Equipment	br1: PaintEquipment	loc: Location	br1.loc = ws1	br1 reservedTo pt1		tk1.loc = tr1.to

Labor	pr1: Painter	loc: Location	pr1.loc = ws1	pr1 reservedTo pt1		dr1.loc = tr1.to
Information	pp1: PaintingPlan		accessible(pp1, pr1)			cn1.loc = tr1.to
Workspace	ws1: LaborCrewSpace	reference: Object orient: Orientation width: Volumetric depth:Volumetric height:Volumetric	ws1.reference = wl1 ws1.orient = side ws1.width = wl1.width ws1.depth = 3m ws1.height = wl1.height	pr1 reservedTo pt1		
Material	pa1: Paint		pa1.loc = ws1			
External	h1: Humidity	value	h1.value < 50%			

Ontological and rule-based constraints reasoning examples

This section demonstrates examples of using the developed ontology (discussed in Deliverable DE.1) and some extended rules to reason for the aforementioned temporal constraints between the activities.

Temporal precedence of activities

Example:

There are two activities: *ex:Drywall1* and *ex:Painting1* for a specific wall *ex:Wall1*. Known as a precedence dependency, for any individual walls, the painting activity can only start after the drywall activity is completed. Because the effect of the completion of drywall activity is that the wall has been installed, which is required by the painting as a precondition (there first should be the wall to be painted).

Thus, in order to implement the ontology and rules to reason for the temporal precedence constraints of the activities, the information/data that required this about the precondition and

The partial RDF triples in the database that represents the information of these two activities are:

```
@prefix ex:<http://example.org> .
```

```
ex:Drywall1 a :Activity .
ex:Painting1 a :Activity .
ex:Wall1 a ifc:Wall .
ex:Drywall1 :addEffect _:e1 .
_:e1 :hasObject ex:Wall1;
  :hasObjectStatus 'Installed'.
ex:Painting1 :hasPrecondition _:pc2 .
_:pc2:hasObject ex:Wall1;
     :hasObjectStatus 'Installed'.
```

A SWRL rule can be set up for this sequencing constraint that the drywall activity should be planned before the painting activity :

```
Activity(?a1)^Activity(?a2)^Wall(?w1)^addEffect(?a1,?e1)^hasObject(?e1,?w1)^
hasObjectStatus(?e1,'Installed')^hasPrecondition(?a2,?pc2)^hasObject(?pc2,?w
1)^hasObjectStatus(?pc2,'Installed')->before(?a1,?a2)
```

Thus, after reason the database with this rule, the sequencing constraints between *ex:Drywall1* and *ex:Painting1* activities is inferred:

```
ex:Drywall1 :before ex:Painting1
```

It must be mentioned, this sequencing constraint of before is transitive, for example:

```
ex:Activity1 :before ex:Activity2 .
ex:Activity2 :before ex:Activity3 .
```

Therefore, the ex:Task1 should be before ex:Task3 as well:

```
ex:Activity1 :before ex:Activity3 .
```

Maximum simultaneous activities

Resource disjunctive temporal constraints

The disjunctive constraints of the resource indicate that two activities with overlapping time intervals cannot use the same resource simultaneously. Assuming there are several activities that their precondition and execution-condition are satisfied, and there are no spatial overlap and precedence dependencies among them. If they require exact same resource, due to the resource disjunctive temporal constraints, they cannot be conducted simultaneously. Therefore, the information/data required is the resource flow information of the activities, in a more simplified explanation, what specific resource the activities are required.

Example:

There are three activities: *ex:Activity1, ex:Activity2, ex:Activity3*. Each of them has its own resource requirement. The following table is the resource requirement of these 3 tasks:

Activity	Equipment	Labor
Activity 1	Crane tower1	General worker crew 1
Activity 2	Crane tower2	General worker crew 1
Activity 3	Crane tower1	General worker crew 2

The partial RDF triples in the database that represents these three activities are:

```
@prefix ex:<http://example.org> .


ex:Activity1 a :Activity .
ex:Activity2 a :Activity .
ex:Activity3 a :Activity .
ex:Cranetower1 a :Equipment .
ex:Cranetower2 a :Equipment .
ex:GeneralWorkerCrew1 a :Actor .
ex:GeneralWorkerCrew2 a :Actor .
ex:ResourceAllocation1 a :AllocatedTo .
ex:ResourceAllocation1 :hasActivity ex:Activity1.
ex:ResourceAllocation1 :hasObject ex:Cranetower1.
ex:ResourceAllocation1 :hasObject ex:GeneralWorkerCrew1 .
ex:ResourceAllocation2 a :AllocatedTo .
ex:ResourceAllocation2 :hasActivity ex:Activity2.
ex:ResourceAllocation2 :hasObject ex:Cranetower2.
ex:ResourceAllocation2 :hasObject ex:GeneralWorkerCrew1 .
ex:ResourceAllocation3 a :AllocatedTo .
ex:ResourceAllocation3 :hasActivity ex:Activity3.
ex:ResourceAllocation3 :hasObject ex:Cranetower1.
ex:ResourceAllocation3 :hasObject ex:GeneralWorkerCrew3 .
```

The resource disjunctive constraints for this case can be translated to the following SWRL rule:

```
Activity(?a1)^Activity(?a2)^AllocatedTo(?at1)^AllocatedTo(?at2)^hasActivity(
?at1,?a1)^hasActivity(?at2,?a2)^Actor(?ac1)^Actor(?ac2)^Equipment(?e1)^Equip
ment(?e2)^hasObject(?at1,?ac1)^hasObject(?at2,?ac2)^hasObject(?at1,?e1)^hasO
bject(?at2,?e2)^(sameAs(?e1,?e2) OR sameAs(?ac1,?ac2)) ->
DisReNonSim(?a1,?a2)
```

Based on this rule, it can be inferred logically that *ex:Activity1 cannot be conducted simultaneously* with either *ex:Activity2* or *ex:Activity3.*

```
ex:Activity1 :DisReNonSim ex:Activity2 .
ex:Activity1 :DisReNonSim ex:Activity3 .
```

Thus, the *ex:Activity1 should be planned before ex:Activity2 and ex:Activity3, or after ex:Activity and ex:Activity3.*

Resource capacity temporal constraints

As previously mentioned, there may be limited resources that constrain the construction activities. If several activities require the same type of resource, in order to inspect whether they can be planned simultaneously, their total required resource amount should be compared with resource limit (the total available amount of resource at that moment). If the total required resource amount exceeds the limit, it means that all the activities cannot be executed at the same time, unless the scheduling method permits some of the activities can use partial required amount of the resource for the execution. This may lead to a result that the activities use the partial resource may be slow down its, but within a tolerable range.

Example:

Assuming there are three activities, which have the resource requirement that shown in the below table. These three activities do not have dependency constraints. Although they require same type of resource, they do not require the specified same resource. The available resource amount of the painters for the following period is **6**. If the required amount of the resource is fixed, it is obvious that all the three activities cannot be executed simultaneously because the total required amount is **8**, but they can be executed in pairs of two. In other words, the maximum number of simultaneous executing activities is 2.

Activity	Resource type	Amount
ex:Activity1	Painter	2
ex:Activity2	Painter	4
ex:Activity3	Painter	2

The partial RDF triples in the database that represents these three activities and their resource requirements are:

```
@prefix ex:<http://example.org> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .


ex:Activity1 a :Activity .
ex:Activity2 a :Activity .
ex:Activity3 a :Activity .
ex:ResourceRequirement1 a :Requirement .
ex:Activity1 :requires ex:ResourceTypeRequirement1 .
ex:Painter a :ResourceType .
ex:ResourceRequirement1 :hasType ex:Painter .
ex:ResourceRequirement1 :hasRequiredAmount "2"^^xsd:double
ex:ResourceRequirement2 a :Requirement .
ex:Activity2 :requires ex:ResourceTypeRequirement2 .
ex:ResourceRequirement2 :hasType ex:Painter .
ex:ResourceRequirement2 :hasRequiredAmount "4"^^xsd:double
ex:ResourceRequirement3 a :Requirement .
ex:Activity3 :requires ex:ResourceTypeRequirement3 .
ex:ResourceRequirement3 :hasType ex:Painter .
ex:ResourceRequirement3 :hasRequiredAmount "2"^^xsd:double
```

This resource capacity temporal constraints are similar with the knapsack problem. Due to SPARQL is lack of the loop iteration functionality, the automatic reasoning for multiple activities (>2 activities) of the resource capacity temporal constraints currently cannot be achieved by only using SPARQL querying and requires external algorithms involved. Moreover, the SWRL rules can also give the answer to this case by comparing the pair of two activities (shown in following table). But it also without iteration functionality, which means it cannot provide an automated and generic solution for multiple activities (>2) as well.

```
Activity(?a1)^Activity(?a2)^requires(?a1,?r1)^requires(?a2,?r2)^hasRequiredA
mount(?r1,?am1)^hasRequiredAmount(?r2,?am2)^swrlb:add(?tam,?am1,?am2))^
swrlb:greaterThan(?tam,"6") ->  DisReNonSim(?a1,?a2)
```

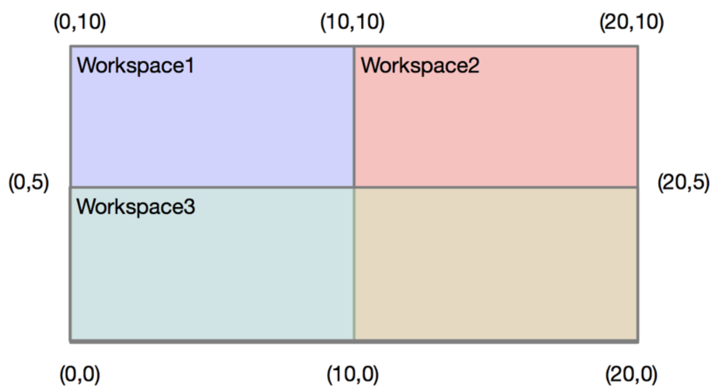
Meanwhile, as previously discussed, sometimes the scheduling method allows the activity to use partial resource to execute, by sacrificing the original planned duration to a tolerable longer duration. It means that the required resource amount for scheduling could be not fixed, if there is available resource left that satisfies with the scheduling requirement for some activities, these activities can still be scheduled. In this case, the minimum required resource amount for the activities to trigger the execution be should considered. For instance, in the previous example, there are 2 painters remaining when we schedule the Activity 1 and Activity 3. If the schedule method allows the Activity 2 to use partial resource, Activity 2 can also be schedule with 2 painters.

Therefore, the resource capacity temporal constraints are more complex than other constraints. Although the current ontology could represent the required information of the resource capacity temporal constraints (the resource requirement), but the reasoning of resource capacity temporal constraints requires a further development of the algorithms and requires external programming out of the scope of Semantic Web and ontology.

Spatial disjunctive temporal constraints

Example:

Assuming there are three activities, each activity requires a workspace for the execution. The distribution of the workspace in 2D is shown in the following pictures.



The partial RDF triples in the database that represents the these three activities and their required workspace geometric representations are:

```
@prefix ex:<http://example.org> .
@prefix sf:<http://www.opengis.net/ont/sf#> .
@prefix geo:<http://www.opengis.net/ont/geosparql#> .


ex:Activity1 a :Activity .
ex:Activity2 a :Activity .
ex:Activity3 a :Activity .
ex:Activity1 :hasObject ex: Workspace1 .
ex:Activity2 :hasObject ex: Workspace2 .
ex:Activity3 :hasObject ex: Workspace3 .
ex: Workspace1 a :location .
ex: Workspace1 :hasGeometry ex:boundingbox1 .
ex: boundingbox1 a sf:Polygon .
ex:boundingbox1   geo:asWKT   "Polygon((0   0,   10   0,   10   10,   0   10,0
0))"^^<http://www.opengis.net/ont/geosparql#wktLiteral> .
ex: Workspace2 a :location .
ex: Workspace2 :hasGeometry ex:boundingbox2 .
ex: boundingbox2 a sf:Polygon .
```

```
ex:boundingbox1   geo:asWKT   “Polygon((10   0,   20   0,   20   10,   10   10,10
0))”^^<http://www.opengis.net/ont/geosparql#wktLiteral> .
ex: Workspace2 a :location .
ex: Workspace2 :hasGeometry ex:boundingbox2 .
ex: boundingbox2 a sf:Polygon .
ex:boundingbox1   geo:asWKT   “Polygon((0   0,   20   0,   20   5,   0   5,0
0))”^^<http://www.opengis.net/ont/geosparql#wktLiteral> .
```

The geometric overlap of the workspace can be identified by using the SPARQL query:

```
PREFIX geo:<http://www.opengis.net/ont/geosparql#>
PREFIX sf:<http://www.opengis.net/ont/sf#>


INSERT {?a1 :WoOvNonSim ?a2}
WHERE { ?poly1 a sf:Polygon .
?poly2 a sf:Polygon .
?poly1 geo:sfOverlaps ?poly2 .
?a1 a :activity .
?a2 a :activity .
?a1 :hasObject ?ws1 .
?a2 :hasObject ?ws2 .
?ws1 :hasGeometry ?poly1 .
?ws2 :hasGeometry ?poly2 .


FILTER(?poly1 != ?poly2) .


}
```

And the non-simultaneously executed activities can be identified and update to the database:

```
ex:Activity1 :WoOvNonSim  ex:Activity3 .
ex:Activity2 :WoOvNonSim  ex:Activity3 .
```

Therefore, due to the workspace overlap constraints, the *ex:Activity1* should be planned before *ex:Activity2* and *ex:Activity3,* or after *ex:Activity* and *ex:Activity3*. Meanwhile, the *ex:Activity2* and *ex:Activity3* are able to be executed simultaneously.

Conclusion

In this section, a common generic data model for communicating the sequencing of work and dependencies between different construction operations was proposed. The key differences to previous attempts to model workflows include the handling of workspace as a resource. Locations of a traditional LBS and workspaces can each have space requirements that are used to calculate space conflicts which prevent work from occurring simultaneously. Traditionally these constraints have been modeled with technical dependencies, although the work could happen in either sequence, just not simultaneously. This becomes critical for decentralized planning and we now move to discussion of a proposed new way to incorporate the knowledge of construction workers. Digitalization of the new process requires the use of new concepts in this section.

The process for decentralized planning

Introduction

This part of the report describes the modeling of a new process for decentralized planning in construction. The process is based on previous theoretical knowledge, as well as on empirical research. The aim was to create a process 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).

Research aim, research questions and methods

To define the process for decentralized takt planning, a practical and explorative approach was taken. First and foremost, the workers' point of view in production planning development has been mostly ignored in previous research. Even though collaborative planning processes (such as the Last Planner System) have been developed, research has been primarily focusing on looking at the issues from the client or general contractor's point of view. Also, research on critically viewing takt production has remained scarce, and the observed barriers of takt implementation have not been reflected in the current takt processes adequately.

Therefore, it was necessary to attempt to cover these relatively fundamental issues for defining the process that could be adequately tested and implemented. For composing the process, the empirical study attempted to answer the following questions:

1. *What are the most significant barriers for effective takt production, and how the found barriers should be tackled in the takt implementation process?*
2. *How to utilize the operational knowledge of the workers in takt production?*

To answer these questions, a qualitative multiple-case study was carried out by investigating the implementation of takt production in six cases. The multiple case study allows to inspect and understand complex social phenomena in its actual context while claiming a holistic approach

(Yin 2014). Moreover, multiple case study approach was chosen to gain robustness and an ability to generalize the results and to increase reliability to extend the usage of the model outside of the circumstances of individual project types and working cultures. Cases included residential, commercial, and industrial construction projects from Finland, Germany, USA California, and Brazil. Data was collected through triangulation, including several semi-structured interviews, supported by a study of project documentation, observation of production meetings, and several site visits. The cases were cross-analyzed, and then discussed in light of the previous knowledge and connected to the results found from the social network analysis. Finally, a model for a decentralized takt process was suggested.

Takt case study results

From the takt implementation case studies, fourteen different barriers for effective takt production were identified (Lehtovaara et al. in preparation, a). Eight of the barriers were related to the planning phase, and six to the control phase:

Most significant barriers related to the planning phase

1. Logistics and material delivery do not meet the requirements of takt
2. The missing integration between structural/shell and interior phases
3. Design management process is not integrated to production planning and/or control
4. Subcontractors are not fully engaged in takt planning
5. Aiming for a technically optimized plan which leads to sub-optimization and resource fluctuation
6. Inadequate drying control while aiming for radical duration reduction
7. Detailed planning focuses only on repetitive areas, while critical path tasks are left to a backlog
8. The contract models do not address the commitment of the individual worker to the overall flow

Most significant barriers related to control phase

9. Common situational awareness is not available for everyone
10. Quality defects result in constant go-back work
11. Effective onboarding phase is not ensured
12. Workers’ commitment, motivation, and stress are not addressed through the production
13. “Making-do” and slipping off takt are not addressed immediately when problems arise

14. No time or resources for problem-solving and continuous development are put in and after projects

From the perceived barriers, six barriers (barriers 4, 5, 9, 12, 13, 14) specifically touched the worker involvement. During the planning phase, insufficient subcontractor involvement in the planning, as well as sub-optimized plans that resulted in resource-inefficiency, were observed as significant barriers. Subcontractors, including superintendents, workers, and heads, generally had a positive attitude towards takt planning. However, it was perceived in several cases that the process and requirements for takt were not communicated adequately to the subcontractor level. Moreover, in some cases where takt was implemented for the first time, GC-led planning resulted in an overly flow-optimized plan which failed to consider the balance between overall flow and subcontractor resource efficiency. This resulted in significant resource fluctuations and difficulties in following the plan accurately. Better involvement would have been crucial to enable subcontractor superintendents plan their resourcing and heads to plan the actual workflow and increase the trust between all production participants. Introducing takt production as early as in the procurement phase and gradually deepening the engagement was suggested for further major improvements.

During the production control phase, major barriers included missing common situational awareness, inadequately addressed worker commitment, slipping off takt, and scarcity of time for problem-solving and continuous improvement. Even though site personnel involvement through visual management was applied in every case, room for improvement was still found in all the cases; for example, by extending the awareness from managerial to the worker level, as well as by supplementing the physical control boards with digital real-time data collection and control. In addition to engaging participants in the planning phase, engagement should be continuously addressed during the production, especially if major problems arise or production crew changes. Otherwise, especially while implementing takt for the first time, slipping off takt to the old ways of working was perceived as a major issue. To avoid chaotic production, more time for problem-solving and ensuring the resources for staying at the pace of takt were suggested as major development points for further takt implementations.

The clashes between top-down and bottom-up plans were seen in takt production quite clearly, as the overall commitment and trust towards the takt plan was not ensured through the production. Instead of opting for the most resource-efficient plan (traditional view to production) or the most flow-efficient plan (lean view to production), planners should find a balance between the two. One takeaway is that the mutual agreement in following the formed takt plan is more important than aiming for the most theoretically efficient plan. Aiming to reduce the gap between 'top-down plan' (GC viewpoint of the plan) and 'bottom-up' (heads' and workers' viewpoint of the plan) could be one of the most efficient ways to reduce waste, as well as utilizing the operational-level knowledge to practice. To model the bottom-up plan, rigid location breakdown structures are not sufficient, because workers tend to think in terms of building elements and space requirements rather than fixed locations.

The proposed process for decentralized takt planning and control

To successfully utilize the decentralization in takt production, the main concern is how to exploit the operational knowledge of the heads and workers during the planning and control processes. Even though takt is sometimes viewed as a strict top-down process, however, if effectively implemented, takt can set clear boundaries for effective decentralized development, for example, within the trains or wagons. Implementing the rough frames for the plan from top-down, followed by bottom-up collaborative detailed planning could offer a way to effectively combine centralized and decentralized ways to implement flow and resource-efficient production plan. In the presented model, we propose a process to address the suggestions. The model attempts to reflect on the best practices to implement takt production (Lehtovaara et al. in preparation, a) while also imitating the most optimal communication and decision-making patterns (Lehtovaara et al. in preparation, b).

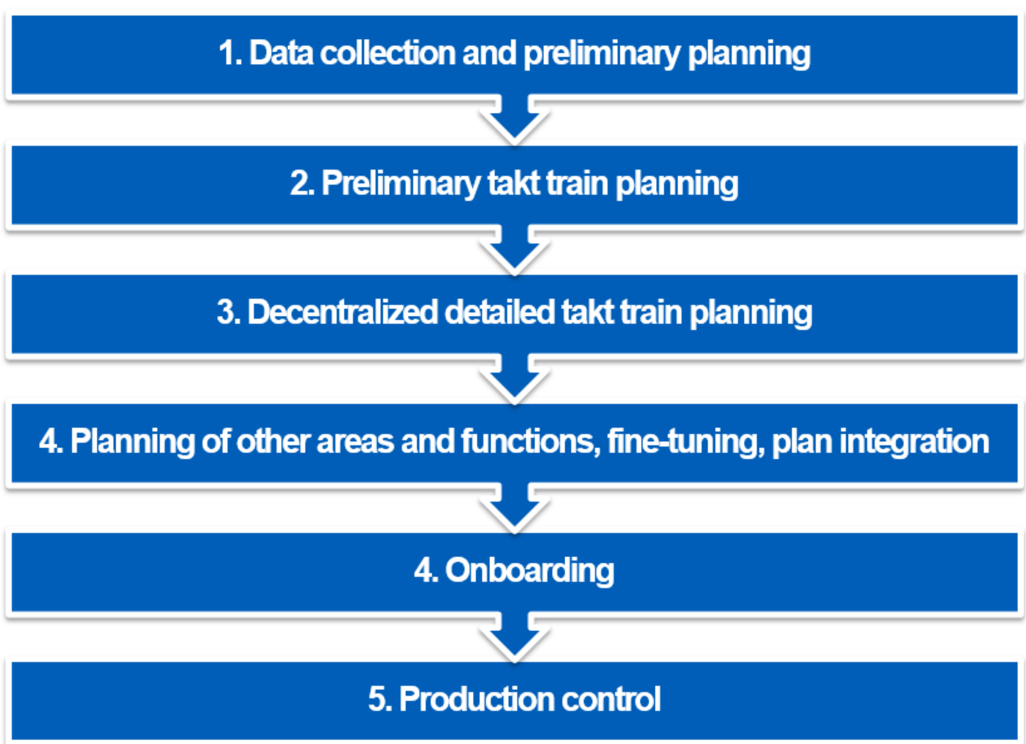


Figure 9

The proposed process for decentralized takt production (figure 9) contains six steps, presented below:

1. **Data collection and preliminary planning:** In the first step, production data (including work steps, quantities, available resources, task durations relative to quantities, and other priorities) is collected, which forms a base for preliminary production planning. This includes defining production scope and milestones based on the client's preferences, as well as defining rough functional areas and the fundamental production flow. The first step is conducted by a 'core' team, including the GC project and site managers, client, and possibly the most relevant contractors if needed.

2. **Preliminary takt train planning:** During the second step, takt areas and takt time are defined simultaneously while defining work packages, wagons, and trains. The preliminary planning phase contains the first iteration for the mentioned takt dimensions, which allows to form the wagon-based team to begin decentralized planning in phase 3. The second step is carried out with the same core team. Takt areas are defined based on traditional fixed location breakdown structures for each construction phase.

3. **Decentralized detailed takt train planning:** At the beginning of the third step, planning teams based on the wagons are formed. The planning team, led by the trade heads responsible for the works inside the wagon, also contain the adequate workers, material suppliers as well as designers (figure 10). 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. Planning includes the iteration of tasks, designs, logistics and sequencing of work within the wagon. Constraints and requirements for other wagons are communicated and the problems with wagon interfaces are solved in collaboration with the preceding and succeeding wagons. In addition, in the iteration process it is possible to iterate takt areas and switch tasks within wagons whenever agreed upon. The idea of decentralization is to simulate the optimal communication and decision-making social networks while enabling the heads and workers to implement their operational knowledge into the plans. The decentralized takt planning phase makes use of workspace requirements which are independent of top down locations but allow the comparison of planning results to top-down plans.

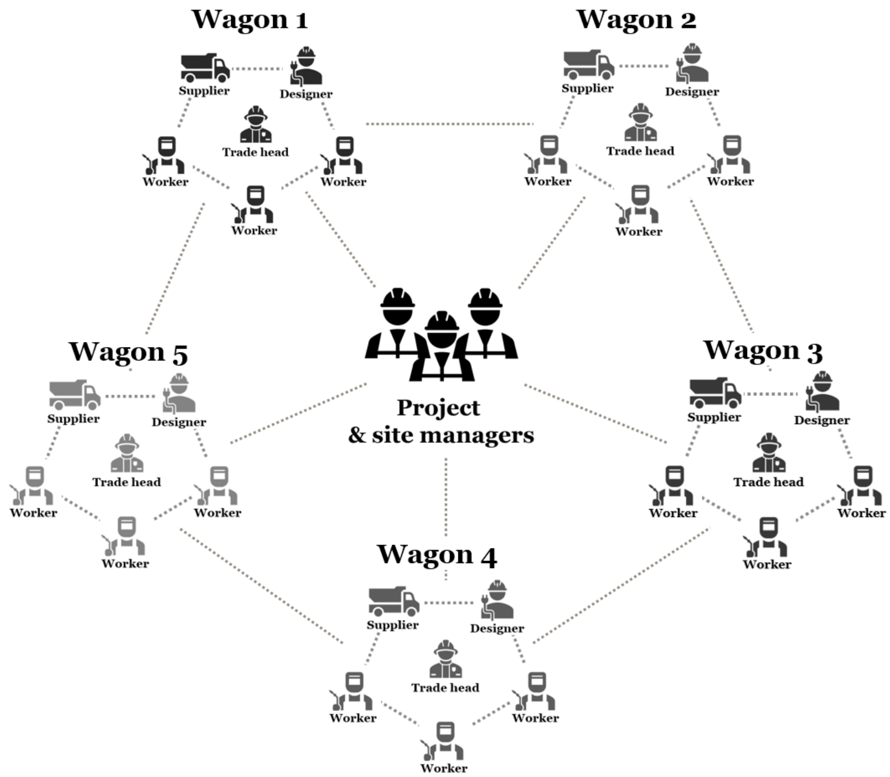


Figure 10: Decentralized planning

4. **Planning of other areas and functions, fine-tuning, plan integration:** After forming the detailed wagon-based takt plan, non-takted areas are included, and 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.

3. **Onboarding**: In the onboarding phase, 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 the final issues before production begins.

4. **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. As presented in Figure 11, the amount of integrated people in decision-making should be gradually increased, representing that the smaller issues should be tackled within the wagons in a decentralized fashion, between wagons, trains, and only after that brought to the

attention of the whole production. The information should always flow through entire production; however, the flow should be ensured by only involving the necessary people in the decision-making process. 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.

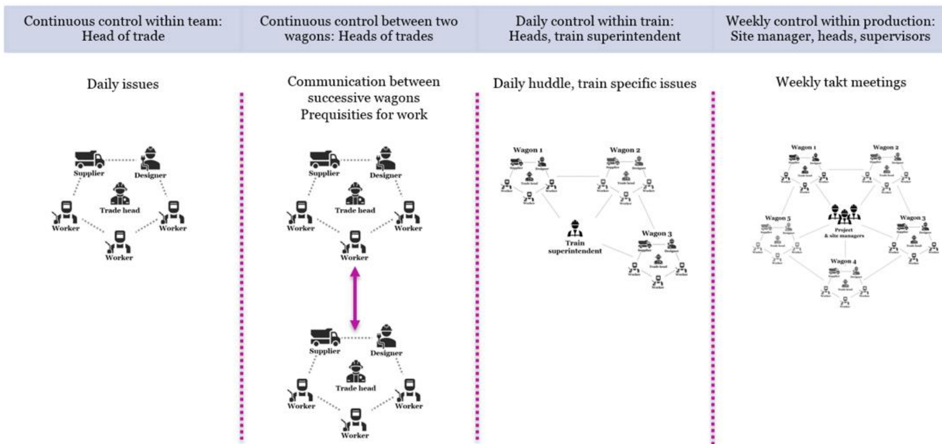


Figure 11 - Decentralized control

Conclusions and future actions

The work aimed to model a new process for decentralized takt planning in construction. The modeled 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 model 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.

Future research needs

This report presents the results of work packages B and C. The proposed processes and ontologies have not been implemented in practice. In particular, there are open questions about what kind of plans workers make and how they can best be digitalized. These questions could best be answered by action research where researchers participate in bottom-up planning and validate the concepts presented in this report.

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