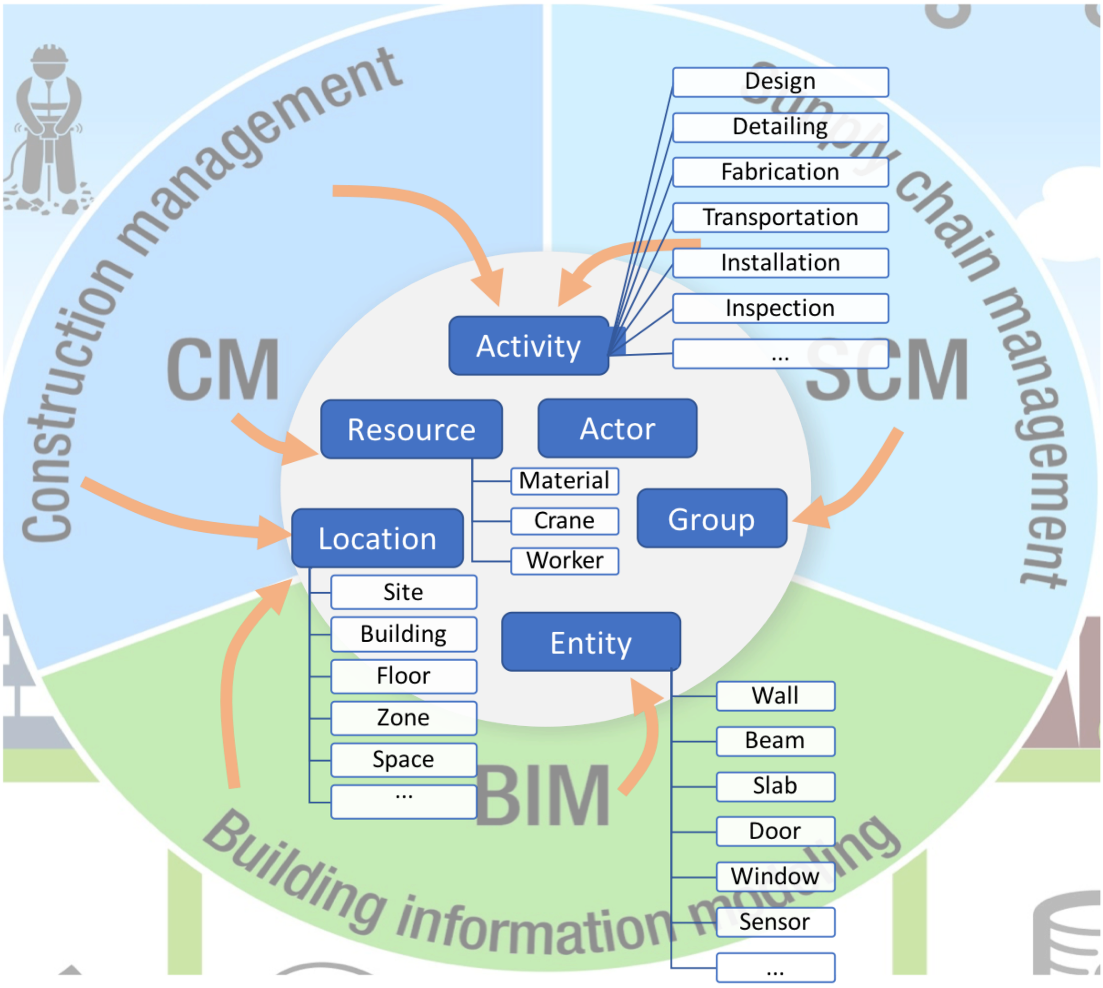

Diction - Deliverable DA.2

Shared situation picture

Requirements for architecture and ontology for information sharing

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Abstract

This is the final deliverable of DiCtion WP1: *A model and ontology of digital construction*. It aims to describe the requirements for the architecture and ontology for shared situation picture of a construction project. It first provides a short overview of the background research areas relevant to a shared situation picture, and then describes the requirements for it, as gathered in the workshops organized in WP1. Finally it presents a concept map of the necessary content of a situation picture and elaborates its central structures. The concept map will serve as the basis for the definition of a common ontology for various systems and data contents that are needed to maintain a situation picture.

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1 Introduction

The overall objective of DiCtion project is to improve the management of workflows in construction projects. The primary goal at the level of information management is to come up with a **shared situation picture**, to support operational planning, progress monitoring, and situation awareness in a project.

At a more concrete level, a shared situation picture is an IT solution that provides all project parties consistent real-time information about relevant status of project execution:

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

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

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

Among the Diction consortium, there has been a particular interest to use the situation picture to support modern construction planning methods such as Takt time planning (Binninger 2017, Heinonen 2016) and LBMS (Kenley 2010), and lean construction practices such as Last Planner (Ballard 2000). These methods and practices introduce specific needs for representing the flows and preconditions of activities, and supporting prediction and work structuring functionalities.

A shared situation picture does necessarily not mean one central system that manages all relevant information within a project. Instead, a more promising approach in long-term would be to base it on a set of interfaces, conventions, and overall architecture that connect existing systems of multiple parties together. Examples of such constituent systems would be BIM platforms/repositories, product data management systems, ERP systems, construction planning tools, and IoT systems.

Such a decentralized setting requires interoperability between systems, and consequently common agreements at different levels of interoperability:

- *Technical*: How systems establish communication relations with each other?
- *Syntactic*: What is the language and format of messages?
- *Semantic*: What terms are used in messages about domain objects and their properties?
- *Pragmatic*: What are the patterns of interactions between parties? How do communication interactions cause activity?

This deliverable focuses on the semantic level: the specification of concepts required to achieve and maintain a situation picture. It is assumed that the technical and syntactic levels can be managed with standard Web of Data technologies. The pragmatic level will be addressed in the forthcoming work.

2 Background technologies

Situation picture can be regarded generally as a *construction model with real-time progress updating* that in addition supports the projection of a situation to near future. It could also be considered as a *digital twin* of the construction process, covering not just the physical objects but also the activities and information objects of a project.

When compared to traditional construction models, the situation picture aims at a much higher level of detail and accuracy, enabled by the proliferation of IoT systems and sensor data on the one hand, and information management technologies for linking existing systems and data sources together, on the other. At the same time there is demand - from the planning practices such as Last Planner (Ballard 2000) - for more accurate modeling of the multiplicity of connections and conditions from which the execution of an activity depends on. In the literature of lean construction these connections are referred to as *flows*.

Below is a short overview of the most important areas of research that address similar questions and challenges as a shared situation picture: *activity flow modeling*, establishing and maintaining *situation awareness*, creating *systems of systems* composed of existing, independent and operational systems, and *Linked Building Data* technologies that provide a common language between constituent systems in construction domain.

2.1 Activity flow modeling

Perhaps the most distinctive characteristic of planning in construction industry, when compared to other industries, is the high deviation of the actual activity execution from the planned one. Less than half of activities are executed as they were planned.

To remedy this situation, many construction companies have during a recent years adopted the Last Planner practice (Ballard 2000) for developing weekly plans. Last Planner is a specific formulation of a planning practice based on the principles of lean construction. The focus of planning is to ensure that activities can actually be started and executed according to the plan.

To achieve this, all the different factors that are crucial to the executability of an activity are checked and brought to hold, one by one. In the literature these factors are alternatively referred to as:

- *preconditions* - states that should hold to enable the start of the activity,
- *constraints* - things from which the possibility to execution the activity depends on, or
- *flows* - things needed by the activity that are released from other activities or sources.

Below these factors are informally referred to as *flows*, despite the problems with that term: it is hard to regard temperature as a flow and in construction things do not flow as they do at the assembly line of a factory. Therefore, in the conceptual model the relations of activities and flows are defined more accurately as *preconditions* (required flow state) and *effects* (released flow state) of activities.

The flows have been divided into more concrete categories, such as:

1. *Labor* - Ensure the labor for executing the activity will be available
2. *Equipment* - Ensure the equipment needed by the activity will be available
3. *External* - Ensure external conditions (temperature, humidity, …) will be appropriate
4. *Component* - Ensure the elements and materials for the activity are available
5. *Information* - Ensure the information (drawings, permissions, …) will be available
6. *Workspace* - Ensure the location for performing the activity is not occupied
7. *Prerequisite* - Ensure the preceding activities have been completed before starting this

It should be noted that a single activity may contain multiple independent flows in each one of these categories. For instance, there can be multiple crews (crane operator, precast installers), equipment (crane, precast supports, …), components (precast element, grating concrete, embeds), and so on. Each of them is an independent flow specific to an activity type and work method used in it.

The concept of flows was introduced by Koskela (1999, 2000). It has been refined into an Activity Flow Model (Garcia-Lopez 2017) that attempts to specify the flow model into more detail, and provides informal concept diagrams that outline an ontology behind the work.

2.2 Situation awareness

An agent has *situation awareness* (SA) when it maintains an up-to-date understanding of the relevant aspects of its environment to enable fast, accurate and correct decision making. SA has been a focus of active study in the domains of military, aviation, and naval control, mostly in single agent settings, and especially in mission critical, real-time decision making situations.

In a holistic framework of situation awareness, Lundberg (2015) distinguishes the following aspects of situation awareness research:

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

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

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

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

Situation awareness has been studied a lot in single agent settings, and especially in mission critical, real-time decision making situations. However, there are also numerous settings where situation awareness needs to be maintained by several agents. When each of the agents has its own situation awareness, there is an overlapping, common part and non-overlapping, complementary parts of that. The common part is called *shared situation awareness* and the complementary part *distributed situation awareness*. Both shared and distributed SA can be important in coordination of potentially conflicting or complementary activities of multiple parties.

An interesting practical realization of situation awareness system in a military setting is the maintenance of so-called *common operational picture*: "A single identical display of relevant information shared by more than one command. A common operational picture facilitates collaborative planning and assists all echelons to achieve situational awareness" (Department of Department of Defense 2018).

2.3 Systems of systems

In all practical settings, the situation picture needs to be implemented as a *system of systems* (Maier 1999). That is, there are a set of pre-existing, independent systems - owned and managed by different participants and serving their original purposes - that will produce information to the situation picture. The implementation of situation picture requires collaboration capabilities from the constituent systems which largely rely on the use of standard languages and protocols.

Examples of constituent systems of the shared situation picture of a construction project are

- BIM collaboration platforms (such as Trimble Connect/World),
- planning and scheduling systems (for instance, Takt time planning or Last Planner),
- ERP systems of fabricators (for instance, precast element or steel structure fabricators),
- IoT/sensor systems (such as indoor positioning, or visual monitoring systems), and
- user tools to record progress information (such as status events).

These systems need to be networked together for the duration of a construction project to server the goal of maintaining the situational picture of the project. This does not imply that data would be copied from the existing systems to some central repository. While the situation picture may need to maintain a central skeleton on the project data in a centralized manner, most of the detailed data is likely to remain in the original systems that provide it for the use of a situation picture system through standard interfaces.

It should be noted that some constituent systems - for instance, the ERP systems of fabricators - can simultaneously participate in several situation picture deployments.

The constituent systems exist before, during and after the construction project, and need to serve their original role and purpose all the time. To make the capable of participating in a situation picture deployment, each constituent systems need to be equipped with interfaces that allows the proper interactions (pushing and/or pulling data) and semantic interoperability with other systems in the context of the deployment.

System of systems is an established engineering displiciple that has also been used to implement situation awareness systems (van de Laar and Tretmans, 2013). General challenges faced in such systems are:

- large volume of data requiring solutions for filtering, focusing, and compression of data,
- historical data requiring the maintenance of large datasets, detection and removal of obsolete data, alignment historical data with changing situations, and keeping integrity and consistency of historical data,
- heterogeneity and independence of data sources, which needs protocol converters, syntax and format transformations, ontology alignment and information fusion,
- conflicts, which creates need to assess trust and reliability of data
- management of privacy and confidentiality of data,
- presentation of data to decision making for human operators in an accessible, manageable, tractable, and visual manner.

2.4 Linked Building Data

The role of Linked Building Data is to provide the common languages, formats and access interfaces that can be used to bridge together different constituent systems that create a Shared Situation Picture deployment. Linked Building Data utilizes the Web of Data technologies specified and standardized by the Web Consortium and applies them to the IFC standards created by buildingSmart International, and standardized by ISO and soon by CEN.

Linked Building Data technologies make building data available on the Web: each building object will have its own Web address (URI) and its properties and relations can be accessed through that address. Linked Building Data is based on a set of previously existing Web standards the most important of which are HTTP, URI, RDF, SPARQL, RDFS, OWL, and JSON-LD. They enable the representation and access to all kinds of structural data on the Web using shared terminologies defined as public ontologies.

Linked Building Data technologies provide a technological approach to decentralized implementations of shared situation picture.

3 Nature of the shared situation picture

3.1 Overall requirements

The particular requirements for situation picture in Diction project are the following. The situation picture should

- focus on the **operational level** - specifically, the execution of construction activities and construction planning ranging from lookahead plans and weekly plans to daily plans;
- cover the **whole extent of a construction project** - including design, procurement, fabrication, logistics, construction, and commissioning;
- establish **connection from sensor observations to activities and actors**;
- support **resource monitoring** of people, equipment and materials to discover what really happens during construction;
- allow the representation of information at **different levels of precision** - enabling the support both for sensor-based data and manually entered data;
- provide **general mechanisms for representation of plans**, such as temporal predicates and the support for multiple worlds (planned, actual);
- include **specific representations for supporting relevant planning methods**, such as Takt Time, LBMS, and Last Planner; and
- represent the **connections of actors** with relevant points of the situation picture - to enable the definition what data is relevant to each actor.

The following areas are at this stage left out from the situation picture:

- Taxonomies and classification schemes - The ontology may provide ways to link to external classification schemes (such as Talo2000, Omniclass, Uniclass, Uniformat, ETIM, ...) but the information included in these schemes is not otherwise included in the situation picture.
- Strategic levels and business models - The information remote to day-to-day situation awareness may clutter the situation picture and can complicate its maintenance, and is not therefore included.
- Access rights - The management of access rights - as crucial as it is - is an important problem that needs to be tackled. However, the exact way it is incorporated in the situation picture will be postponed to the next version of the model.

3.2 Questions to answer

The situation picture should provide answers to following questions of actors:

- What is the current status of activities relevant to me?
  - What activities are ongoing and what have been completed?
  - When activities need to be completed?
- What is the status of entities relevant to my activities?
  - For instance, models, documents, drawings, building elements, temporary structures, resources?
- What will be the status of activities and entities in near future?
  - What activities can and should be done during the next period?

  - Will the preconditions and execution conditions of activities be satisfied?
  - Will the necessary resources will be available?
- Are there any issues relevant to me that I need to attend to?
  - For instance, delays, insufficient resources, broken equipment, failed activities?

Some examples of use scenarios for a situation picture are the following:
- Guidance of activities - A site worker needs to check what are the next activities he should be performing and where. What is the information (models, drawings, specifications). What are the conditions of different flows?
- Week planning - The planning team needs to check what activities are in the lookahead plan and create a plan for next week. The preconditions and execution conditions of each included activity must be checked and actions to establish them be identified. The plan is completed and committed to the situation picture.
- Precast supplier - A precast supplier has access to a constantly up-to-date information about the work status at construction site and can use that information to schedule the fabrication to prioritise the urgent deliveries, which is easier since there is more flexibility with the non-urgent deliveries.

3.3 Interactions with other systems

Some example interactions between existing systems and a situation picture deployment are shown in Figure 1.

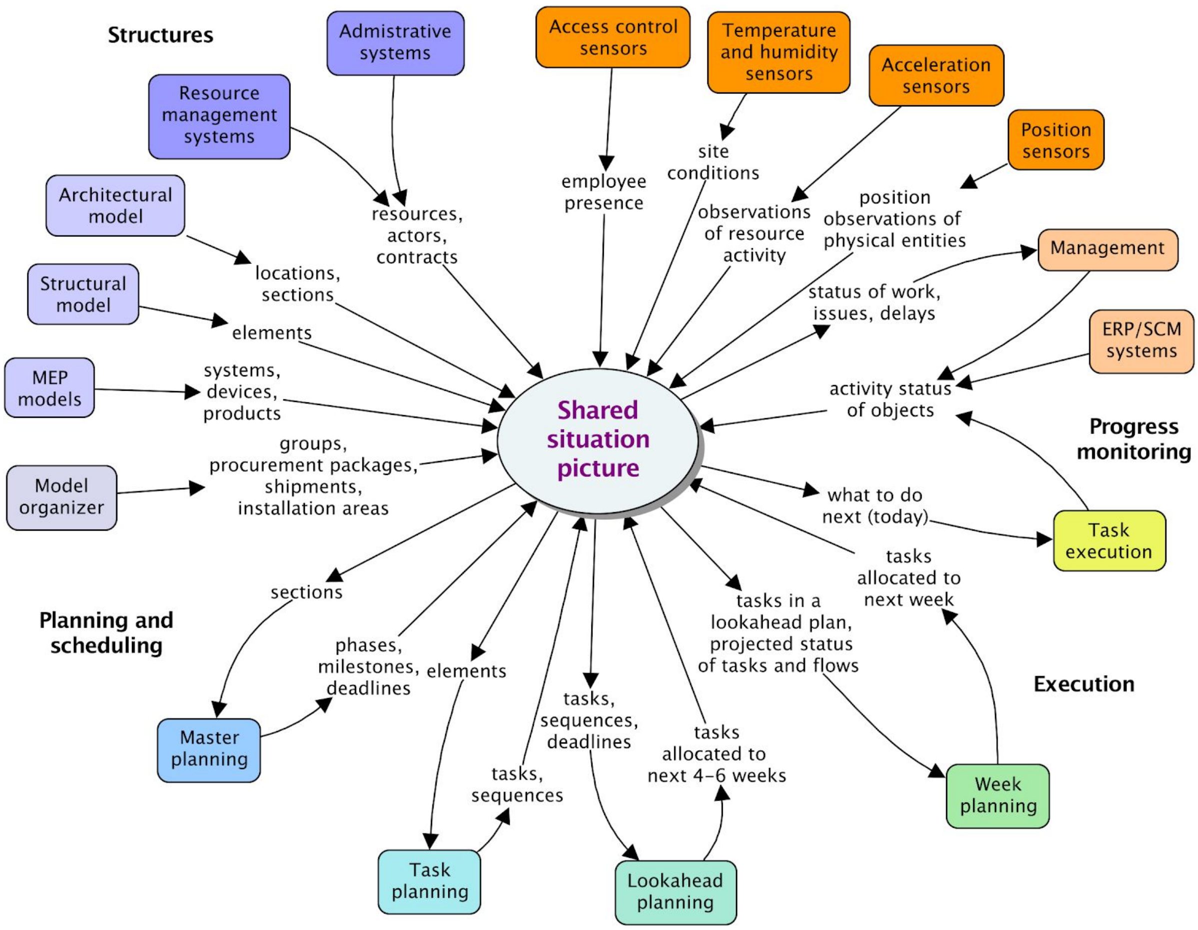

Figure 1 - Interactions of situation picture

The inputs of situation picture can be divided into following types:

- Static or slowly evolving structures - For example:
    - BIM models and their evolution through more specific LOD levels
    - Parties, organizations and contracts in a project
    - Master schedule of the project, specifying its main milestones and deadlines
- Regularly updated plans - For example:
    - Task planning, specifications of workflows
    - Lookahead plans and weekly plans
    - Resource planning
- Real-time or frequent progress events - For example:
    - Sensor data
    - Status events from managers and workers
    - Updates from ERP or SCM systems

It should be noted that the information acquired through the different channels has very different nature. First, the slowly evolving information can be regarded as a background of the situation picture that over the time gets more refined but not in a totally linear manner. There can also be disruptive changes due to changing requirements, inter-model conflicts, or other problems such as correction of errors or omissions. However, its overall evolution is characterized by increasing level of detail and level of development.

Second, the planning activities create new plans - master plans, lookahead plans, weekly plans - that present increasingly refined, concrete, and committed intentions for the execution of value-adding activities. The role of this information is to coordinate and guide the work to be done. The generation of the data is periodic and based on rolling time horizon.

Finally, the real-time data from sensors and activity execution provides information describing how the activities actually got executed and what is the status of different building elements and resources. Overall, this kinds of information flows in as a constant stream of small events.

The planned/designed and actual information are often regarded to belong to different worlds in a sense that their relation to reality is different. Moreover, different plans each define a different world. The planning, coordination and later analysis of activities require the capabilities to manage information belonging to these different worlds, and to relate information across them.

The particular challenge in construction is that the planned and actual worlds can be much farther from each other that in other areas of industry (e.g., in manufacturing or in industrial projects). This means that a simply idea - used for instance in many project management software - that actual activities are in practice the same as planned activities, perhaps with slight deviations in start and end times, works poorly in construction projects.

Since less than half of activities are executed as they have been planned, the actual execution generally differs so much from the planned one that the attempt to represent it with just by adjusting actual start and end times of planned activities can completely obfuscate what really happens.To understand the situation, the actual activities need to be recognized. Situation picture should therefore support the recording of information from which the actual execution can be derived. This means the positions and activity status of activities.

4 Overview of the conceptual model

The overview of the situation picture as a concept map is shown in Figure 2 below. The central concepts are shown in a darker color.

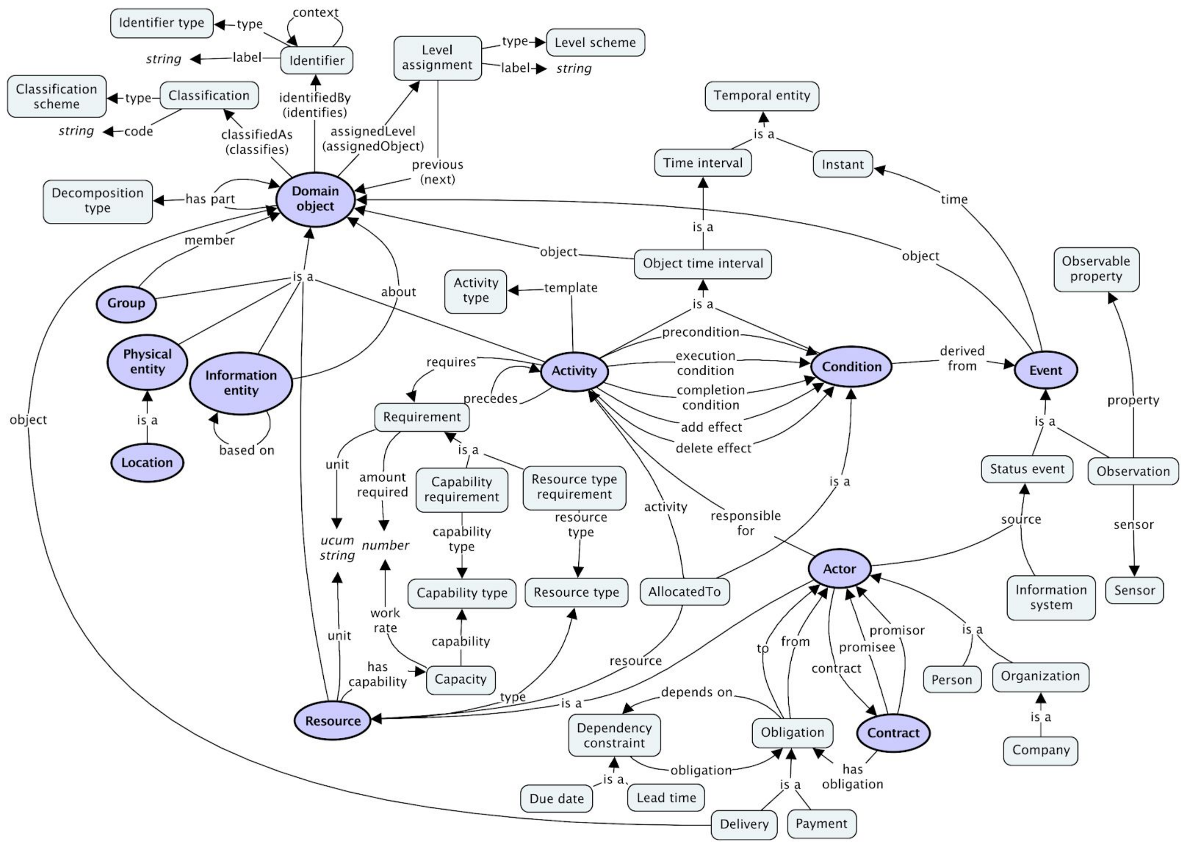

Figure 2 - Concept map of a shared situation picture

In the following the different parts of the concept map are explained in more detail.

4.1 Domain objects - relations and subclasses

Domain objects (Figure 3) mean all the central objects that are discussed in the construction project planning and management: entities, activities, resources, and so on.

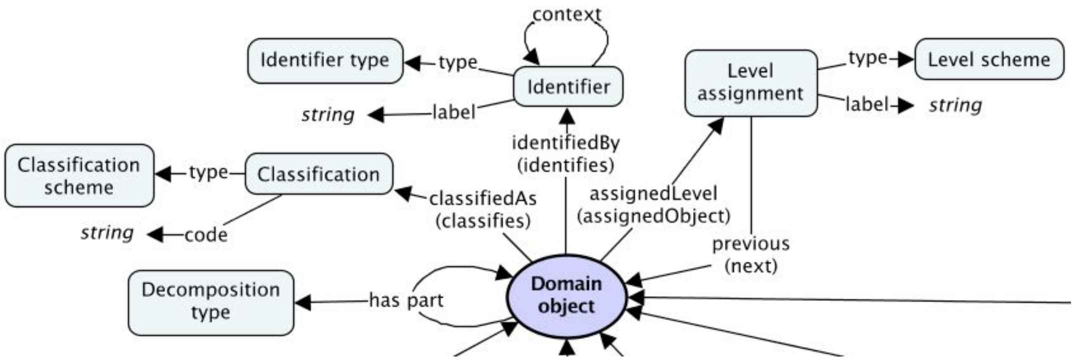

Figure 3 - Domain object and its relations

Domain object has the following relations:

Domain object		
Relation	**Value type**	**Description**
identifiedBy (inverse: identifies)	Identifier	Unique identifier that can be used to separate the object from others within the situation picture. In an open system like situation picture, the identifiers should be globally unique (such as a GUID/UUID). In addition an identifier can be retrievable (such as a URI) which means that it can be used to retrieve information about the object. A domain object may have several different identifiers (such as a GUID and a URI) for different purposes. An identifier can also be a local one, in case it has a specified context with respect to which it is evaluated. Examples is a room number that is unique within the context of one building.
classifiedAs (inverse: classifies)	Classification scheme	A domain object can have an association to multiple different classifications (such as Omniclass, Uniclass, Uniformat, freeClass, Talo84, Talo2000, ETIM). The class identifier in each of these classifications can help to access other related information (specification, guidelines, standards) within the particular classification domain.
assignedLevel (inverse: assignedObject)	Level scheme	An object can be assigned a level from any possible level of detail, level of information or level of development scheme. An objects can have multiple simultaneous level assignments, for instance, concerning the levels of geometry, information, documentation, and development (commitment). A level assignment has a possible link to previous (next) level in the particular level scheme used in the assignment. For instance, an object may be assigned level 300 in the BIMForum LOD scheme, and the assignment can refer to previous object that has an assigned level 200 in the same

		scheme.
hasPart (inverse: partOf)	Domain object	Each domain object can have multiple simultaneous breakdowns into smaller parts. Different decompositions are relevant for different activities. Each decomposition has a type but no limits in the levels of breakdown structure or naming of different levels.

It should be noted that already the representation of this information content is very valuable:

- Unique identifiers provide a naming mechanism and "names make connections" (Saltzer and Kaashoek, 2009). They are essential in enabling linking between systems, data and users, and are necessary for building more advanced functionalities on top of a situation picture.
- Classifications codes make it possible to connect domain-specific type information to objects. The situation picture itself is not - and should not be - dependent on any particular classification but the creation of data in a particular deployment of situation picture may depend on information specified in a particular classification.
- Level assignments provides a partial support for level of details, developments and so on within the situation picture. There is still more work to do for simultaneous maintenance of the model information at the multiple different levels.
- HasPart relations can be used to represent different kinds of breakdown structures that are used in construction projects, such as Product Breakdown Structure (the decomposition of the building to floors, spaces, and building elements), Work Breakdown Structure (the decomposition of a construction project into subactivities ranging from project phases to individual construction tasks, as well as others such as Location Breakdown Structure or Organization Breakdown Structures. HasPart relations have been studied intensively in the field of mereology (Varzi, 2003, 2015). As a relation HasPart is:
    - reflexive: hasPart(x, x),
    - transitive: hasPart(x, y) & hasPart(y, z) => hasPart(x, z)
    - anti-symmetric: hasPart(x, y) & hasPart(y, x) => x = y

The domain object is a general class that covers the entities in models as well as activities in plans.

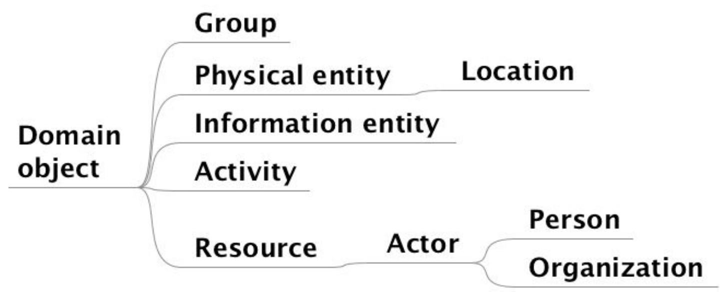

Figure 4 - Subclasses of domain object

The subclass tree of Domain object are shown in Figure 4. In the following is a short description of each subclass:

- *Physical entity* - Any object that has physical dimensions and a position. Examples include building elements, building products (devices, windows, doors), physical resources, material packages, and so on.

    - Location is a subclass of physical entity that has a special role in some construction management methods. Examples of locations are all spatial elements such as spaces, floors, zones, buildings, and sites. In a similar manner than other physical entities, locations can also have multiple simultaneous breakdown structures.
- *Information entity* - An object that carries information, such as a BIM model, drawing, specification, message, and so on. In an organized activity, such as construction, the information objects are *about* some other objects, that is, they contain information about those objects. Information entities can also be based on other information entities, in a manner that they utilize and/or rely on information in those other entities.
- *Group* - A superclass for all kinds of groupings of objects, such as procurement packages, shipments, installation areas, fabrication lots, and so on. Groups are often created because some activity is carried out at the same time for all members of the group. Groups have members, which is a similar relation as hasPart but not exactly the same.
- *Activity* - A superclass for all work (or aggregations of work) carried out in a project. An activity can represent everything from a project and a project phase (e.g., design, construction) to elementary tasks. As activity is a subclass of time period, all activities have start time, end time and duration. Activities can also have subactivity (subproperty of hasPart) and precedence relations with other activities. There is also a set of relations that are specific to lower level tasks that deal with flows, such as preconditions, discussed in a more detail below.
- *Resource* - Those objects within a construction project that participate in value-adding transformations but that are not ultimately transformed themselves. Examples of resources are machinery such as cranes, equipment such as drills and tools, and temporary structures such as forms, railings or scaffoldings.
    - Actor is a subclass of a resource, capable of taking responsibility of activities. Actors are divided into Persons and Organizations. Actors can have relations established as Contracts.

The Domain object and its subclasses form the backbone of the information in the situation picture.

4.2 Activities, flows and conditions

Since one of the main purposes of the situation picture is to give the understanding of the status and progress of a construction project, the concept of activity has a central role in it. Moreover, as the situation picture is specified to take advantage the fast developing sensor capabilities, it is crucial to be able connect activities to sensor observations. Furthermore, since the situation picture is designed to support the Last Planner practice, the model should provide a possibility to represent the various flows related to activities.

To satisfy these starting points the relations of flows with an activity are represented as conditions of flows. Instead of referring to a flow - such as *crew* - directly in an activity, it is referred to indirectly through a condition called *allocatedTo*. Likewise, to capture the flow of an *element* in an installation activity, the condition is that element is *atLocation* installation location.

In addition to capturing the relation between flows and activities, Condition is also a way to capture the semantically meaningful interpretation for sensor observations. Most of the sensors deal with physical objects or phenomena, not activities directly. It is therefore most natural to connect sensor observations to the Conditions of physical objects.

Condition is a concept to capture a semantically meaningful state of an object, such as its location or temperature at a level that is needed for construction management. Condition is a subclass of time period, which signifies that the state of the object can evolve over time and have different values at different times. In some modeling approaches Condition could be called a temporally qualified relation, meaning a relation that assumes different values at different time periods.

As Figure 5 shows, the commonalities of Activities and Conditions relate to their temporal nature: both are time periods. They are also both related to some object that is their focus. In addition, there are a number of relations between them. Activity has the following links to Condition:

Activity		
Relation	**Value type**	**Description**
precondition (inverse: enables)	Condition	The conditions that need to hold before the execution of an activity can start. The preconditions thus enable the execution of the activity. Examples of preconditions of transportation activity are that the object to be transported is at the start location of the transportation, and that the vehicle used in the transportation is at the start location, and that the vehicle has the capacity to carry the object.
execution condition (inverse: supports)	Condition	The conditions that need to hold during the whole execution of the activity. Examples are resource-type flows: that crews are allocated to activity, that workspace is allocated for the activity, that equipment are allocated and at the location of the activity.
completion condition	Condition	The conditions that need to hold to enable the completion of an activity. For example, the transportation is completed when the vehicle is in the end location, or casting is completed when the concrete has been hardened. The completion conditions together form the "definition of ready" for the activity.
add effect	Condition	The conditions that the execution of the activity establishes. For instance, the execution of a transportation activity establishes the condition that object is at end location, or installation establishes the condition that the status of the object is installed.
delete effect	Condition	The preconditions that are removed as a result of the activity. For example, the object to be transported is no more in the start location.
precedes (inverse:	Activity	Activity precedence relation. (This and other similar relations will likely be inherited from Time interval). The

follows)		precedence relations can be mostly inferred from the flows between activities.

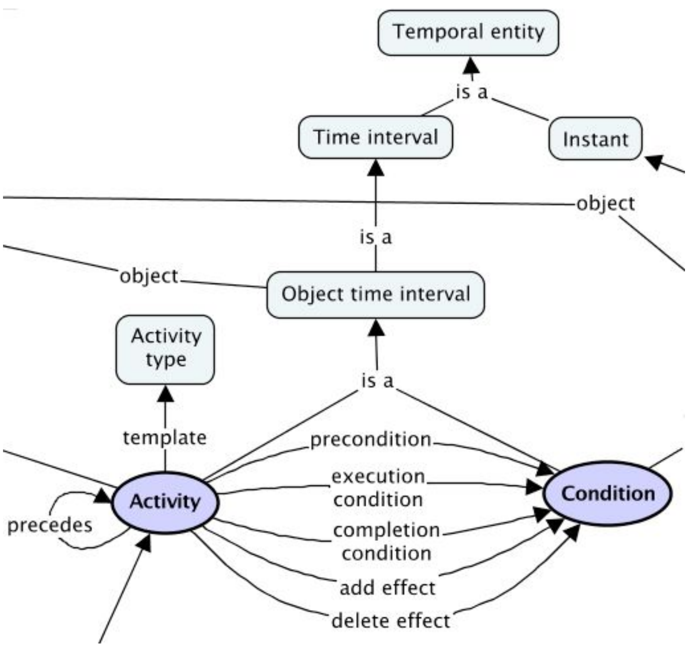

Figure 5 - Activity and condition

The flows - as well as the conditions in which flowing objects need to be - needs to be specified for each activity type specifically. There is material available for that in construction recipes such as Talo2000 Ratu-cards and other similar sources. The following provides some initial examples what kinds of information needs to be provided about activities to capture the necessary flows. The examples are written as ActivityType definitions in a pseudo-code that specifies the name of a new activity type, the superclasses, parameters, and relations to various conditions. The conditions are inherited from supertype to subtypes, so that subtype has a union of all its own conditions and those of the supertype.

```
define Activity (DomainObject)
 - preconditions:            {}
 - executionConditions:      {}
 - completionConditions:     {}
 - removeEffects:            {}
 - addEffects:               {}

define Transport (Activity) (?object ?startLocation ?endLocation)
 - preconditions:            { (?object atLocation ?startLocation) }
 - removeEffects:            { (?object atLocation ?startLocation) }
 - completionConditions:     { (?object atLocation ?endLocation) }
 - addEffects:               { (?object atLocation ?endLocation) }

define VehicleTransport (Transport) (?object ?startLocation ?endLocation ?vehicle)
 - preconditions:            { (?vehicle atLocation ?startLocation) }
 - executionConditions:      { (?vehicle allocatedTo this) }
 - removeEffects:            { (?vehicle atLocation ?startLocation) }
 - completionConditions:     { (?vehicle atLocation ?endLocation) }
```

```
 - addEffect:              { (?vehicle atLocation ?endLocation) }

define VechicleTransportLimited (VehicleTransport)
                                  (?object ?startLocation ?endLocation ?vehicle)
 - preconditions:        { (?object weight ?weight)
                           (?vechicle loadCapacity ?maxLoad)
                           (<= ?weight ?maxLoad) }

define Install (Activity) (?object ?whole)
 - preconditions:      { (?object installed false)
                         (?object atLocation ?location)
                         (?whole atLocation ?location) }
 - removeEffects:      { (?object installed false) }
 - addEffects:         { (?object installed true) }
```

Once activities have been created based on these kinds of templates, they have connections to appropriate flows. In Figure 6 below is an example activity: a Transport activity "Transport-1" that takes the Precast-group-1 from Fabricator-1 to Site-1.

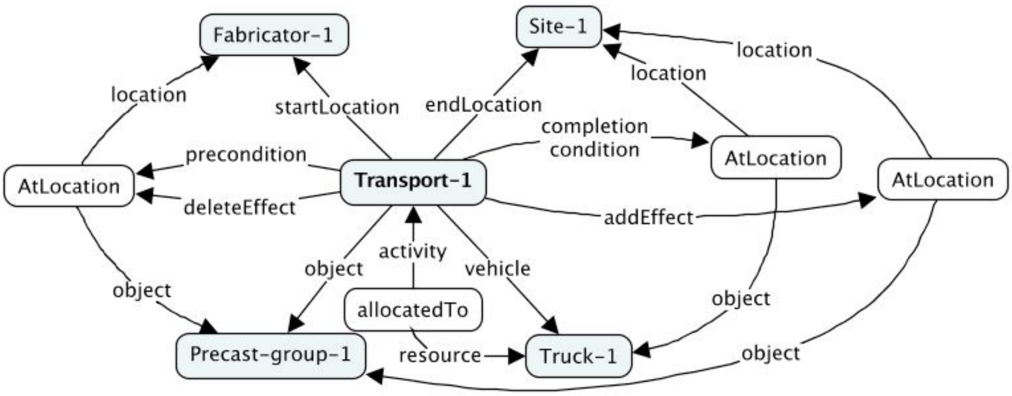

Figure 6 - Transport activity "Transport-1" to take Precast-group-1 from Fabricator-1 to Site-1

The connections from activities to flows - and especially the meaning of connections that the conditions specify - facilitate the development of support for Last Planner type planning practices, as well as utilization of sensor information in the

4.3 Resources and requirements

The relations between Activity and Resource are relatively complex, as shown in the Figure 7. Activity may require several different types of resources for its execution. The resources allocation allocatedTo is represented as a Condition that refers to the resource that was allocated, activity to whose execution it was allocated, and the time period (inherited from Condition) for the duration of allocation. These relations are all relatively straightforward since they are between instances in a situation picture.

The representation of resource requirements is much more complex, since activities typically do not require any individual resource instance but any suitable type of resource will suffice. For this reason, the Requirement has to be abstract, allowing the specification of a category of resources.

In the conceptual model there are two ways of doing that. A Requirement can either be a Resource type requirement or a Capability requirement. The former one specifies a Resource type that can be for instance a "Painter", "Precast installer" or "Crane operator". An example of the latter one could be "painting".

The traditional approach is to use resource type requirements, to specify for instance that an activity requires two painters. A more fine-grained approach is to use capabilities to specify that the activity requires the capability of painting for 100 m^2. One of the advantages of capability-based requirements is that a single resource could have multiple capabilities that could be matched with requirements individually.

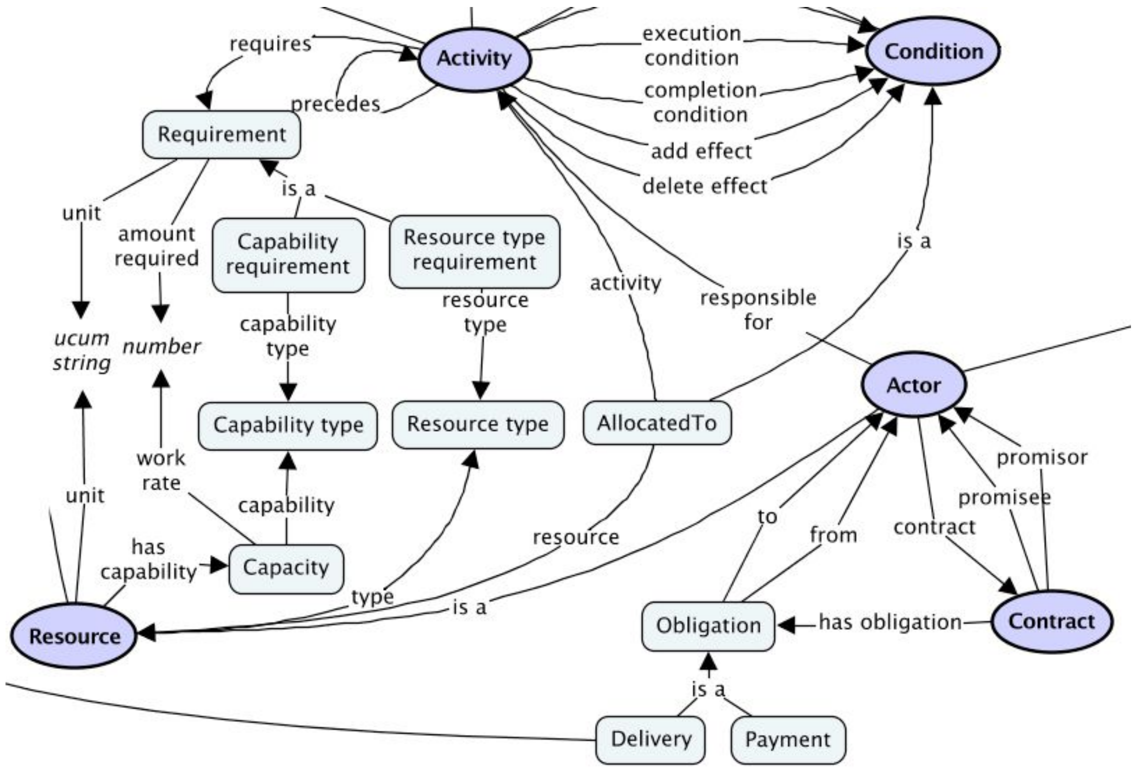

Figure 7 - Resources, requirements, actors, and contracts

Associated with capability requirements are resource capacities that enable the resource per resource specification of the work rate in specific capability.

One subclass of a Resource is Actor that can assume responsibility for Activities, in addition to being allocated as resource for them. Possible subclasses of Actor are Person and Organization, and Company a typical subclass of Organizations. These distinctions are not represented in the conceptual model but they could become important if the access control issues would be managed using the concepts of the situation picture.

Actors can be in contractual relationships with each other. Contract is modeled as a sequence of obligations between contract parties. Subclasses of obligations are Deliveries and Payments.

4.4 Gathering and interpreting progress data

The progress data (Figure 8) can arrive to the situation picture as *events* in a form of *status events* or *sensor observations*. The source of status events can be a human users - such as a construction worker or a site manager - who updates status information using a mobile tool. Another source for status events are systems such as ERP or SCM systems of different actors, or even the access control system to a construction site. Sensor observations can originate in a range of different kinds of sensors, measuring for instance position, acceleration or temperature. The raw measurements typically arrive to situation picture through a layer of sensor or IoT middleware.

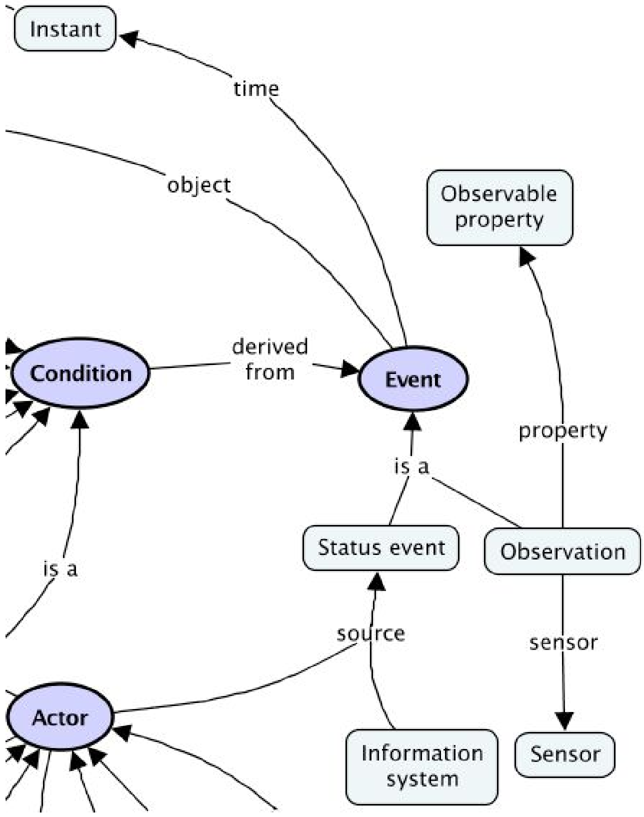

Figure 8 - Sensors, status events and conditions

The processing of event can be described with the situation awareness levels:

- *Perception* - The reception of events to situation picture represents perception, the first level of achieving situation awareness. There can be a level of filtering of events - especially sensor observations - that are obviously erroneous (e.g., occasional faulty GPS coordinates that would require unrealistic a speed of motion from the sensor).
- *Comprehension* - Understanding the events in relation to the expectations of a situation, which means that the events are interpreted against the prevailing plans. This involves several steps:
    - Filter and prioritize the events that are relevant to ongoing, open activities. For example, some received events can relate to elements that were needed for activities already completed and approved; these events can be archived but must be pruned out so that they do not clutter the comprehension processes.

    - Map the events to expected conditions at the granularity required. For instance, detailed positions (e.g., GPS coordinates) should be smoothed and if possible, mapped those semantically meaningful locations (e.g., site storage, lifting area) that have been referred to in plans. Also if a plan specifies a specific temperature range for a casting operation, the temperature observations should be mapped to this semantic value range.
    - If mapping to expected conditions indicate deviations from the prevailing plan, these deviations should be "highlighted" in the current situation. Critical deviations should direct the attention; e.g., managers could check the situation more closely.
    - The comprehension can also include detection of cues that evoke frames that represent special unplanned situations, such as machine breakdowns or broken elements.
- *Projection* - The situation is projected into future to reveal the implications to the remainder of the plan or to the next planning cycle. The projection at this stage is deterministic, for instance, consisting of the propagation of time bounds of activities based on the critical path method. At this stage scheduling decisions - for instance, resource allocations - are not changed and activity sequences on resources would be maintained. In the sense projection simply tries to show what will happen if no new decisions would be made.
- *Prediction* - The external and random factors that can affect the future are combined with projection to achieve more realistic image of the coming situation. This can include the empirically determined variability of flows and activities, as well as likelihoods of events such as weather problems.

The model creates a pathway to connect sensors to construction management, through the chain of links:

- Sensor -> Observation -> Condition -> Activity -> Actor

The links in the chain may each require reasoning - filtering, fusing, and mapping of data - but the pathway can nonetheless be established.

5 References

Ballard, H. G. (2000). *The Last Planner System of Production Control*, Doctoral dissertation, University of Birmingham.

Binninger M., Dlouhy J., and Haghsheno S. (2017). “Technical Takt Planning and Takt Control in Construction.” In: LC3 2017 Volume II – Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC), Walsh, K., Sacks, R., Brilakis, I. (eds.), Heraklion, Greece, pp. 605–612. DOI: https://doi.org/10.24928/2017/0297

Department of Department of Defense, 2018. *Dod Dictionary of Military and Associated Terms: 2018*, Createspace Independent Publishing Platform.

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

Garcia-Lopez, N, 2017, *An Activity and Flow-based Construction Model for Managing On-site Work*, Doctoral dissertation, Stanford University

Heinonen, A., and Seppänen, O. (2016). “Takt Time Planning: Lessons for Construction Industry from a Cruise Ship Cabin Refurbishment Case Study” In: Proc. 24th Ann. Conf. of the Int’l. Group for Lean Construction, Boston, MA, USA, sect.2 pp. 23–32.

Kenley, R. and Seppänen, O., 2010. *Location-based Management System for Construction: Planning, Scheduling and Control*. London and New York: Spon Press.

Koskela, L. J. (1999). “Management of production in construction: a theoretical view.” 7th Annual Conference of the International Group for Lean Construction, Berkeley, CA, 241–252.

Koskela, L. (2000). “An exploration towards a production theory and its application to construction.” VTT Publications 408, Espoo, Finland.

Lundberg, J. 2015, Situation Awareness Systems, States and Processes: A holistic framework.

Nofi, A.A., 2000, *Defining and Measuring Shared Situational Awareness*, Center for Naval Analyses, Alexandria, VA.