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CONSTRUCTION OBJECTS RECOGNITION IN FRAMEWORK OF CPS

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ABSTRACT

Recent breakthroughs in BIM and ADC technologies promise innovative solutions to bridge the information gaps between the digital models and real construction site. These solutions promote the collaboration between digital, spatial and physical construction. Cyber-physical systems offer a tight integration between real physical and virtual "cyber" models. This collaborative approach supports the digital transformation in construction domain. A cyber-physical framework is proposed to provide consistent relationships and allow bidirectional data flow. In the framework the recognition of objects successes by linking physical objects to the digital product models using RFID. Next, these objects are equipped with global positions data and pinned to semantic and functional enrichment construction places. The results are objects at a level of "smartness" with enhanced digital capabilities and the ability of context-awareness. The cyber-physical objects are embedded in the process models in order to support tracking activities and facilitate process monitoring and control close to real-time.

1 INTRODUCTION

Investigation of digitally-driven strategies for making things is crucial in order to bridge the gap between the physical construction and the digital models based on sensing and emerging technologies (RFID, GPS, Laser scanning, etc.). A breakthrough has been done using Building Information Modelling (BIM) technology that can extrapolate into a digital fabrication strategy. Nevertheless, the granularity relationships and connectivity between the digital models and physical fields of practices have to be discussed carefully to close the information loop and establish a tight cyber-physical bi-directional coordination in construction.

The recent advances in Automated Data Capture (ADC) and BIM facilitate the integration of physical construction of spaces and objects into virtual information models which in turn allows a bi-directional data flow in a near real-time.

Formally Cyber-Physical systems (CPS) approach is about conjunction between the physical world of objects and digital "cyber" world of software and computing. Similar to the pioneer role of CPS in industry 4.0 initiatives, CPS approach can be seen as a promising paradigm for digitally driven technological fusion in construction sector. Thereby the objects and processes of site operations tied directly to the digital building models using automated data capture techniques. The CPS likewise internet of thing (IoT) gain currently an increasing attention being to support a bi-directional coordination and integration between virtual construction of models, software and services and real construction site of components, machines and crew. This leverages the digital collaboration toward smart built environments.

The work describes a CPS framework closing the information loop between the digital models and real physical objects on-site. Therefore, feedbacks about objects and related activities are timely available for simulation, decision-making and optimization. Three integration methods are proposed to fulfill objects recognition in the framework and keep a consistent relationship between the physical entities and their digital twins: (i) stable cyber-physical link establishment, (ii) equipping physical objects with temporal position data, and finally the objects are pinned to (iii) explicit spatial and semantic enrichment construction work areas where diverse objects interact.

In the CPS framework, objects and information are inextricably linked and no longer differences between information and physical items especially in the context of flow. Cyber-Physical objects (CPOs) have a centric role in the framework, in which objects and construction processes are mutually-influencing. In this manner process and objects will be inseparable, i.e. physical things become part of the process. The CPOs in the proposed framework are distinct by identity, status, behavior and/or action derived based on a mathematical algorithm and logic. Finally, the CPOs data are smoothly integrated to support construction processes discovery, simulation and planning in near real-time fashion.

2 RELATED WORK

CPS were envisaged originally in computer science as next wave of innovation in ICT enables a new generation of "smart systems". It has drawn great attention by academia and industry due to its environmental and economic impact (NIST 2013). Beyond the embedded system, CPS is open, multi-scale and designed as a network of interactive components more than standalone devices (Talcott 2008; Lai et al. 2011).

CPS is the backbone of industry 4.0 initiative, the concept has been promoted in Germany to highlight the work of more efficient, intelligent and sensor-rich manufacturing facilities. Smart factory as a part of industry 4.0 revolution refers to the efficient and optimized manufacturing industry in which the CPS is adopted for tracking and monitoring of a product throughout its life cycle (Kagermann, Wahlster, and Helbig 2013).

In construction and infrastructure domain, the potential of using CPS solutions is promising especially for monitoring and control problems during project lifetime, namely construction, maintenance demolition. However, it is still a challenging task due to the complexity of developing a CPS approach includes beyond the physical layer and human-machine at lower level, a networks layer and computing capabilities. Although, there are several approaches are proposed to integrate sensing technologies with BIM for progress and assets tracking, logistics and safety on-site as in (Azimi et al. 2011; Teizer, Cheng, and Fang 2013; Motamedi et al. 2013). However, the semantic of collected data was only partly available in some cases. Besides, the IFC extension for RFID are not yet supported by BIM tools or the pairing BIM with RFID was based on expensive active solutions (Akanmu, Anumba, and Messener 2013). The fact is an insufficient interlinking of BIM and real physical construction lead to less scalable and reusable cyber-physical models. Hence, it is necessary to specify the integration level, i.e. to what points the real physical construction coexists with BIM models.

3 CPS FRAMEWORK

The goal is to use the CPS concept for smoothly integrating the real physical construction entities into virtual information models controlled by semantic rules. The rules and relationship between systems components are to accomplish a consistent bi-directional coordination and integration.

Figure 1 depicts a solution bundles different aspects and facets from different domains into a generic framework conceptual model. The framework provides a closed loop for information interoperability and interaction among all sub-systems. It proposes a system based on CPS approach with new capabilities allowing the individual entities of different parts to work together. The embedded objects in the framework of CPS are at a level of "smartness" with enhanced digital capabilities and context-aware content (i.e. location, time and date, behavior and action). Abstractly, the framework comprises basically:

1. Cyber construction gives a classified and semantic enriched BIM models beyond the design phase with a tight connectivity to the real construction products. The semantic enrichment, annotation and /or linking elementary models according to multimodels (MM) method (Fuchs and Scherer 2017) leverage the virtual models in order to create digital twins which are a virtual equivalent of

physical entities. Hence, cyber construction represents the maturity of the digital object-oriented product and/or process which is supposed to be at a level of development (LoD) realizing BIM onsite.

2. Physical construction: It comprises the physical places and resources:
   - Physical objects (resources) refer engineered materials (prefabricated components, modular elements, etc.), equipment, machine and even personnel on-site.
   - Construction site is a place where the physical construction entities are processed. Site spatial entities describe roughly the construction site boundary, neighborhoods and work zones.
3. Data management, analysis and computation methods are curial to handle and filter the raw facts of the physical construction. the aim is to change raw data into meaningful information and in advance into "smart data". The smart data are designed to play an actuation role within the system. For instance, at process level, a specific recommended action can be arranged as soon as a well-described event occurs which is derived by handling the site raw data.
4. Knowledge and services: This facet is an access point, where the cyber-physical objects are integrated and interacted to deal with real-world problems. Thereby the bi-directional coordination between the real world and digital models are accomplished by monitoring (physical→cyber) and control (cyber→physical).

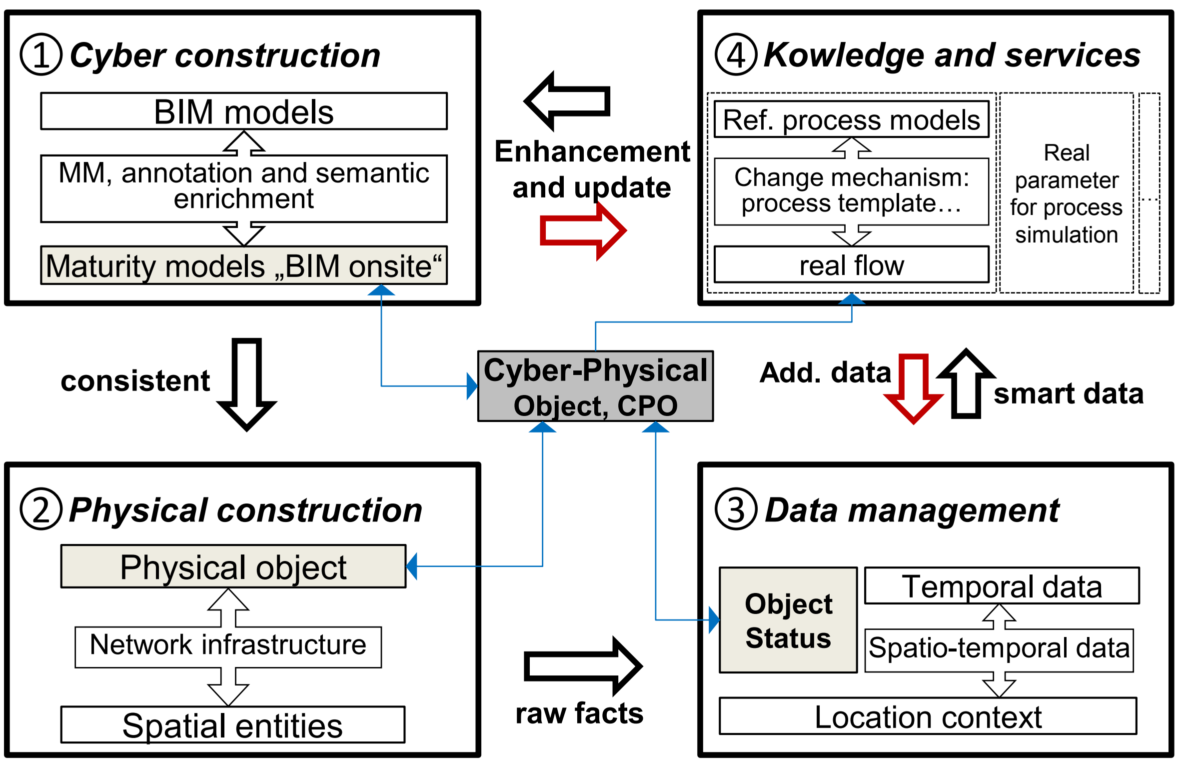

Figure 1: A cyber-physical integration framework conceptual model

4 CYBER-PHYSICAL OBJECTS

The discussed CPS framework inducts consequently embedded construction objects that have specific characteristics namely, digital representation, context-aware information and connectivity. Those three fundamental features encapsulate the definition of CPOs in our approach and make them different from other conventional objects (Figure 2). According, a CPO is a physical thing at a level of smartness with digital representation, unique ID, and situational awareness.

Generally, smart objects in the era of CPS and IoT can understand and react to their environment (Kortuem, et al. 2010). They are shifting the interconnectivity from human-to-content and human-to-device into content-to-content and device-to-device levels, e.g. GPS unit updates the content automatically based on object's location.

The representation of CPOs refers that each element has a size, function and property sets, and a semantic relationship within the virtual information models. This representation or model element can be extracted and filtered out from BIM models. The context-aware property characterizes the location where physical objects are processed at which time-window and what state/ behavior they have. These provide an interpretation for events and activities with respect to predefined processes (reference process models). The interconnectivity refers particularly to the ability of unique identification of individual object during its lifetime. It shall allow "bi-directional" interaction between construction components, their digital twin. Objects recognition methods in the CPS framework that are necessary to keep a consistent relationship between virtual and physical construction are summarized in:

- Cyber-physical product link establishment: It ensures physical construction objects to be uniquely identified and tracked in on/ off site up to installation and verification.
- Association of objects and global positioning: It means each physical object is being pinned to an approximate temporary global location that is inherited from a reading-node position.
- Extracting semantic location from construction site is to conquer the limitation of the ADC methods, like a passive RFID system, by leveraging the semantic content of captured data.

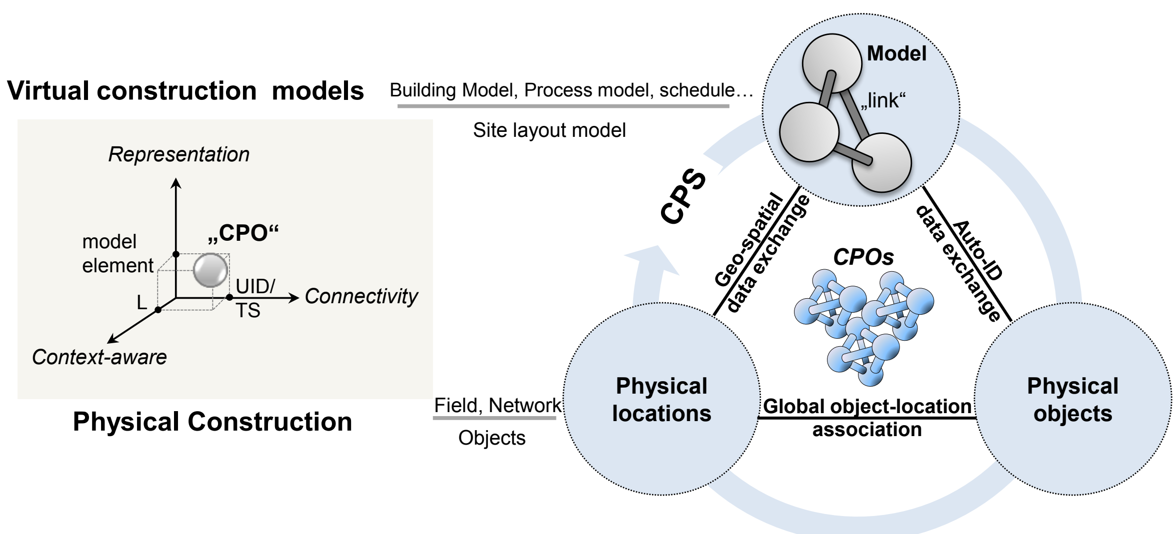

Figure 2: Cyber physical-object, CPO concept.

5 CYBER-PHYSICAL PRODUCT LINK ESTABLISHMENT

The focus is on linking physical objects uniquely using RFID with the cyber construction at the level of items (i.e. model element) (Figure 3). In addition, a rich semantic model has to prepare in order to establish the cyber physical objects, thereby every element in the model describing a specific physical element during product life cycle. The data enrichment method allows a consistent and unique identification of the element from fabrication over logistics until installation and later verification at jobsite. The work proposes IFC data standard (ISO 16739:2013) to pairing RFID, while the IFC model:

1. contains an object-based inheritance hierarchy (e.g. wall, column, beam, door)
2. offers IfcPropertySet an interesting feature of IFC model which allows adding user-defined properties to IFC elements or types.

These specifications of IFC model facilitate the necessary interlinking task. However, the current IFC standard is limited for RFID, thereby a direct link between RFID and IFC has not yet supported. Although there are a few efforts to extend IFC data model to incorporate RFID directly (i.e. new classes and attributes) like a standard definition of RFID systems in BIM proposed by (Motamedi et al. 2013), yet the adoption, standardization process and implementation of the new IFC schema in BIM authoring software will take a long time to complete.

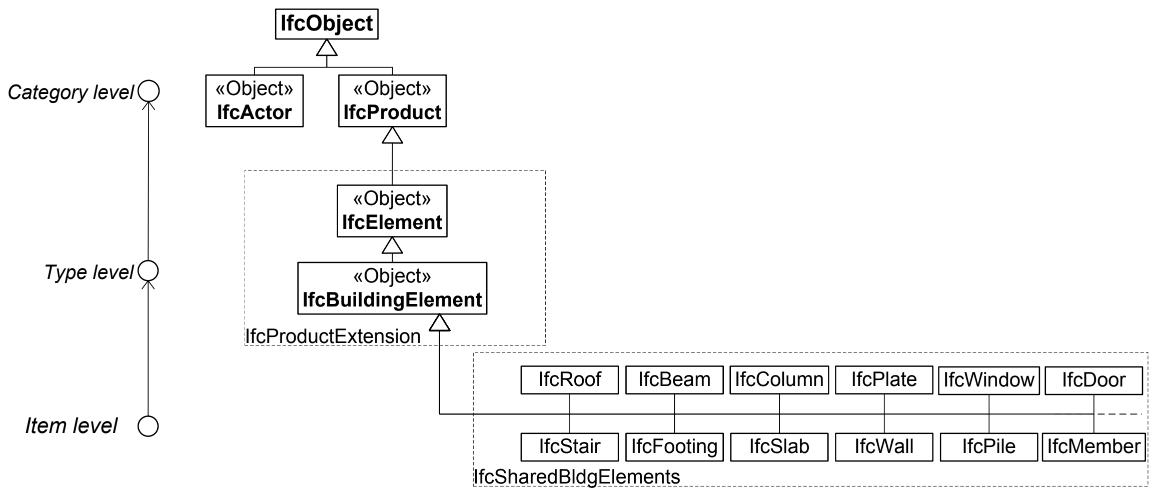

Figure 3: IFC hierarchy relevant to RFID interlinking.

Alternatively, RFID data are added as user-defined property sets to IFC elements based on a standard schema to create a consistent link between the physical component and its model element. Thereby, every model element can be equipped with RFID Tag data like a unique serial no, EPCgloble (RFIDTagID, GlobalTradeItemNumber, etc.). The new property sets are stored in a reference database for annotation. This work uses a web-based tool for annotation and data enrichment “BIM-Annotator” developed in institute for construction informatics in Framework EU Research Project Bridge-Cloud.

BIM-Annotator serves two purposes:

- Enhancing the quality of IFC model by annotating the elements with correct attributes and user-defined properties,
- Adapting a model-level granularity according to classification method (e.g. Omni-class, Uniclass, etc.) and level of details, e.g. grouping several element to create a component with new properties reflects the real case of physical entity in logistics (palette or individual component) and installation on-site.

The reference database for classification and data enrichment is deveopled based on the XSD schema of Property Set Definition (PSD) of buildingSMART which includes basically a list of all IFC classes and templates for property sets (Ismail et al. 2016). Figure 4 depicted the BIM-Annotator user-interface for RFID data enrichement.

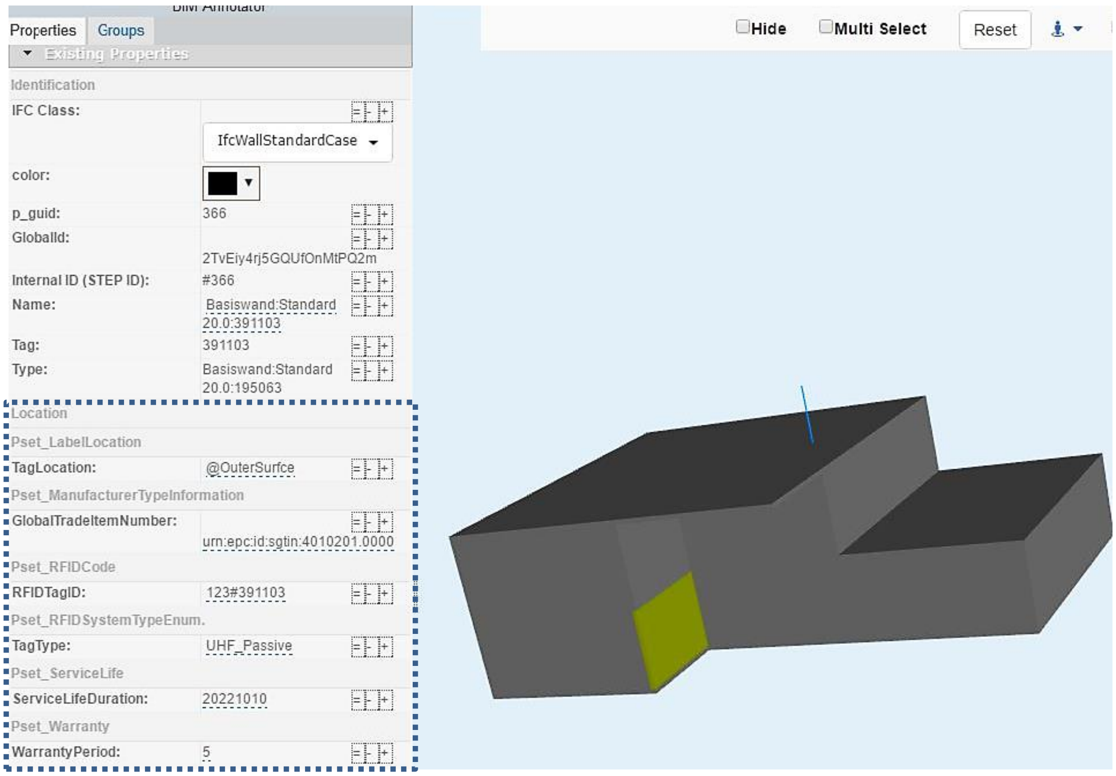

Figure 4: BIM-Annotator user-interface, extending the property sets of a wall element with RFID data.

6 SMART BUILT-ENVIRONMENTS

The construction site is usually a temporary limited manufacturing place for related buildings. Moreover, the construction site is beyond the location where the construction processes are taking place, an interface among all project parties. Leveraging the content of site aggregated data to generate CPOs need a place recognition model including elements identification with their temporary position. Next, mapping the objects to semantic locations (i.e. functional work zones) equips objects with a context-aware content.

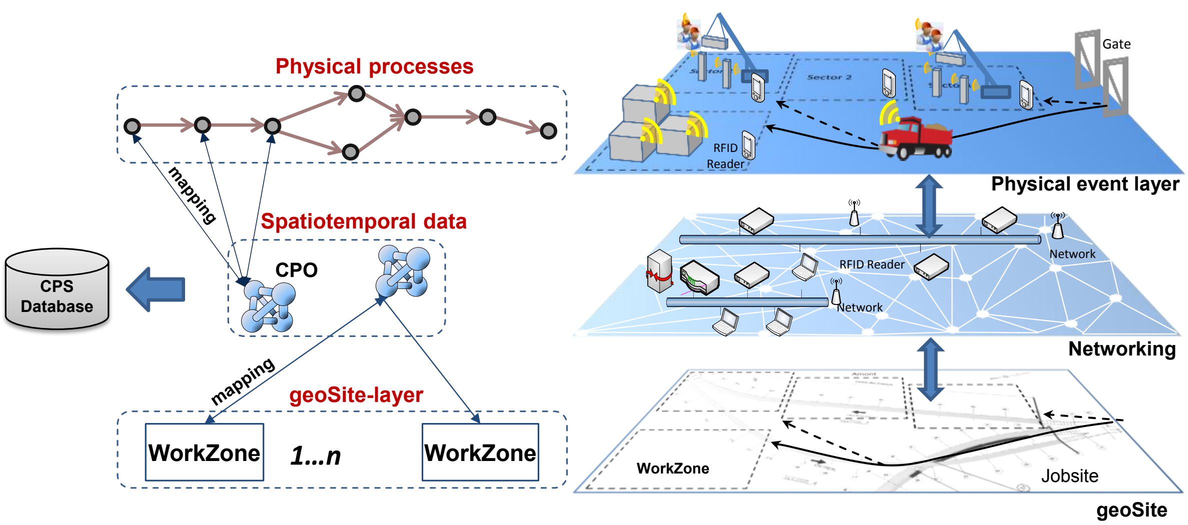

Figure 5: Virtual construction site based on a layers model and functional work zones.

Figure 5 depicts a layers model for construction places recognition, in which the construction site decomposes into three characteristic layers simplifying identification and integration of complex construction site entities (Srewil and Scherer 2013):

- Physical event layer, it represents the real construction site where the processes take place.
- Networking layer, it is a kernel in which the two other layers are fused.
- geoSite, it brings the semantics to the physical location where site data are captured.

6.1 geoSite, location-context information enrichment

While dealing with longitude, latitude and altitude only cannot interpret the semantic of objects locations, the geoSite approach is to determine site spaces and associate them with functional information over a specific time window. The geoSite model determination requires:

- Extracting basic spatial data of construction site related spaces,
- Location context establishes by linking the site schedule to the site layout plan.
- Designed constraints are necessary to control the relations among work zones themselves and the whole site with neighborhoods

A site schedule is crucial to deal with site dynamic features. Here, site spatial data sets are limited to the level of details that provide site boundary and work zones as a conceptual model (i.e. horizontal 2D footprint or 3D block). Figure 6 depicts a workflow for identification of geoSite, it includes:

- Site layout geometry are described by the footprints derived simply by vertical projection.
    1. IFC file is used to retrieve site spatial data and building footprints using a set of filters and mathematical operations (Figure 7).
    2. Extended work areas which do not exist in the IFC model by user-defined inputs given either as a bounding box (MBR) or 2 D - 2.5 D Geo spatial data as coma separated value (CSV), OpenStreetMap, LandXML, etc.
- Site schedule provides the important dates and context to create site layout plan.

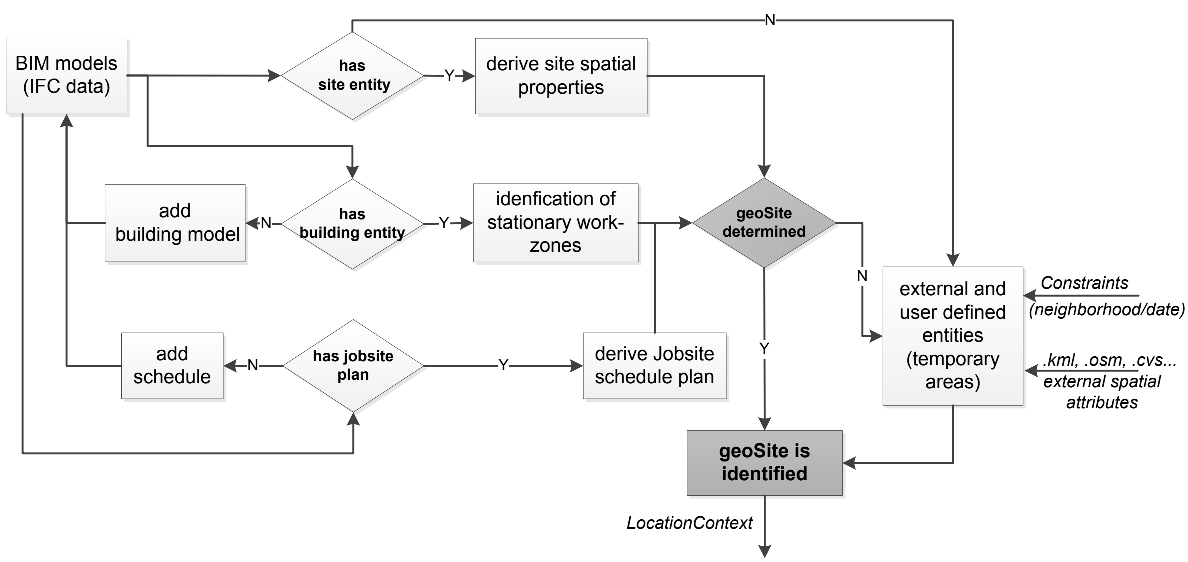

Figure 6: Flowchart for construction site identification and extracting location context data.

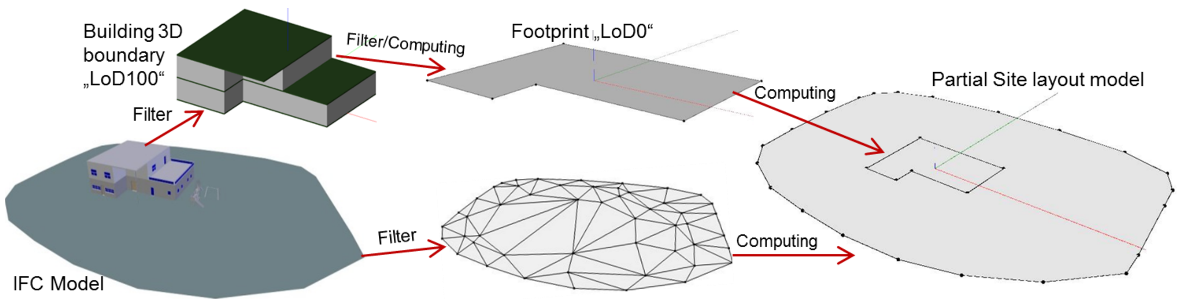

Figure 7: A case example for extracting site layout geometry (simple polygon) from IFC model.

The geoSite shifts the complex construction site into a set of functional oriented spaces. Four distinct entities formulate geoSite:

- LocationContext: It is a labeling class representing the semantic category (*Ci*) for a construction site which gives an implicit function of a location, e.g. "storage" where elements are stored.
- TempWorkZone is a 2D polygon that sizes a temporary work area with specific function over specific time window, for example "Laydown-Block XYZ", "Gate" and so forth.
- Building refers generally a stationary facility that has unchangeable location in project lifetime and represented by the footprints.
- The ConstructionSite encapsulates all TempWorkZones and Building, and it is the destination of all off-site shipments.

The relation among diverse entities and between neighborhoods is described using a constraint which is sets of rules defined by the user and/ or related authority and standard (e.g. DIN 18299: 2012-09). Constraints are satisfied based on a suitable mathematic logic.

Generally construction site and work zones topology have to satisfy some common definition and constraints as the following:

- A geoSite G_S envelops all work zones and is described as a collection of functional areas, i.e. a family of subsets:

$$G_S = \bigcup_{i=1}^{k} A_{Fi}$$

$A_{Fi}(P_i, C_i, t_1, t_2)$ is a work zone with a specific location context category (C_i) represented as polygon, a set of a planar cartesian points $P_i(x_i, y_i)$, over a time interval $[t_1, t_2]$ then:

$$\forall A_{Fi} \subset G_S \leftrightarrow \forall a(x,y) \in A_{Fi} \rightarrow a \in G_S$$
$$\exists\, a`(x`,y`) \in A_{Fi} \wedge a` \notin G_S \leftrightarrow A_{Fi} \not\subset G_S$$

- Overlapping free constraints:
  1. Overlapping free with neighborhoods: Let P is a 2D polygon describing any neighboring of a site and A_{Fi} is a specific work zone onsite then: $\forall A_{Fi} \subseteq G_S \wedge \forall P \not\subset G_S \rightarrow A_{Fi} \cap P \equiv \varnothing$.
  2. Overlapping free among work zones at a time *(t)* are: $\forall\ (A_{Fi}, A_{Fi+1}) \subset G_S \rightarrow A_{Fi} \cap A_{Fi+1} \equiv \varnothing$

6.2 Data capturing solution

The work proposes ultra-high frequency (UHF) passive RFID system. Among others, the system has excellent features for the identification of static or even moving products, machines and personnel in a harsh environment, at a cost- efficient infrastructure. It encompasses:

- Passive RFID tags are fixed to physical elements for identification; therefore, tags should be designed with maximum possible level to be reached, read and protect from noise and interference.
- Reading-nodes or readers (stationary and/or handhelds with built-in GPS receiver).

The readers play multiple roles within the system. They communicate with tags to collect item identification data and are used to equip collected data with positioning information (reader localization manually or based on a built-in-GPS unit) for ultimate system capability. Two event types are expected:

Definition 1 *Recording-event (Rec_E) is an observed RFID reading given as a tuple* $Rec_E=(Tag_{ID},R_{ID},TS)$ *This event takes place as soon a transponder is in a reader range.*

Definition 2 *Reader-event (R_E) is a spatial-temporal event and defines also as tuple* $R_E=(R_{ID},R_{POS},TS)$; *R_{ID}: the reader ID, R_{POS}: the reader position at timestamp(TS) of a Recording-event. Such event is triggered if a reader changes its current position, the new position can be specified manually or automatically. by GPS.*

The position of the readers will allow determining the position of a scanned physical object by matching both event types and returned object *ID*, position and timestamp *TS*. Furthermore, the duplicated RFID data are filtered out by matching the Tag_{ID}, R_{ID}, and *TS* of an event-node such complex events management and filtering are taken place in the system middleware. Figure 8 illustrates a schema that can be used for events generation based on readers at discrete locations on-site.

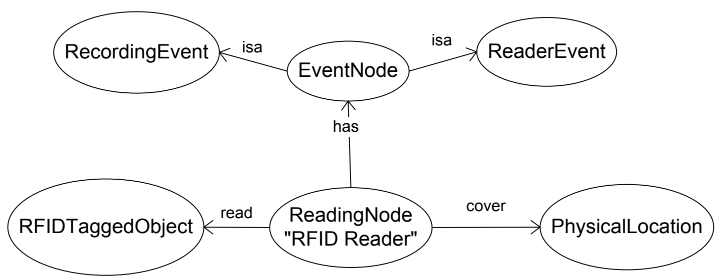

Figure 8: Data capturing model.

6.3 Mapping of geoSite and Network layer

A mathematical algorithm is used to map the reading-nodes of network layer into geoSite G_S layer an envelope of all work zones and building which have a specific location-context C_i as formulated in equations (1) and (2): Let $n(R_{POS},t)$: is a reading-node in network N at a position R_{POS} and time t:

$$\{\forall n \in N \mid n \text{ LocatedAt } (R_{POS},t) \in A_{Fi} \wedge A_{Fi} \text{ Is-a}(P_i,C_i,t_1,t_2)\} \rightarrow n \text{ Has}(C_i,t);\ t_1 \leq t \leq t_2 \quad (1)$$

Furthermore, n belongs to a specific work area A_{Fi} when:

$$\forall n \in N : \exists n \in A_{Fi} \subset G_S \leftrightarrow \begin{cases} PIP_n = 1(n inside A_{Fi}) \\ PIP_n = 0(n directly\ on A_{Fi}) \\ PIP_n = -1(n outside A_{Fi}) \end{cases} \quad (2)$$

Where: PIP_n is a well-known Point-In-Polygon test of a point n and polygon A_{Fi}. According to the definitions 1 and 2 above, all physical components in the range of a reading-node n inherent its location on-site at the same time interval. This approximation is justifiable via the proposed scenario in an outdoor environment and a limited reading range of the passive RFID system (roughly up to 5 meters). However, an accurate localization of an object is measurable using advanced sensing approaches such as ultra-wideband (UWB) or RSSI-based system (Kamel et al. 2011).

For example, let an object Obj_i is read by a node n at a time t at a laydown yard $A_{Laydown}$, then $Obj_i \in A_{Laydown}$ and therefore Obj_i is stored on-site. Contrary, if $A_{Fi} \subseteq G_S$ and $n \notin A_{Fi} \rightarrow n$ and all Obj_i in the range are off-site. Furthermore, if an Obj_i is identified by several readers at different places simultaneously then the accurate location of this object may determine by a trilateration algorithm. The ontology schema in figure 9 describes the relationship among the reading-nodes, location context and diverse construction site areas. The location context information is used to derive the object status (S_{Obj}).

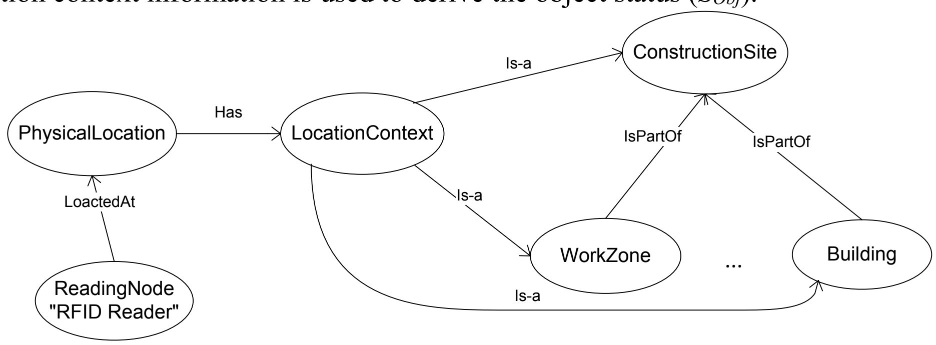

Figure 9: Mapping of RFID system and semantical site layout model.

7 CPO INTEGRATION IN THE CONSTRUCTION PROCESSES

The focus is on an object-oriented process model. CPOs are involved in the business process being the actual entities of a process model. They are modeled as a data object in a process model. The definition of object expresses at least a unique *ID* and a status S_{Obj} attribute. Figure 10 depicts the relationship between a CPO and a process. The current status of an object S_{Obj} at a time frame t is derived by matching the object position and location context of a work area where the object is identified (cf. equation (1)).

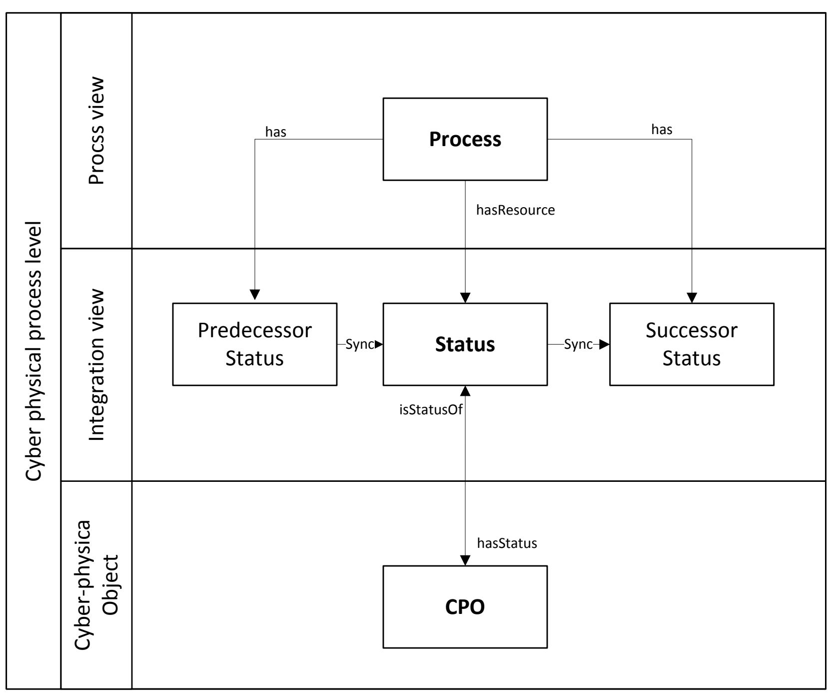

Figure 10: Process and object status ontology model.

Therefore, the state of the object changes as this object has left one work zone to the next one. Let: a task *T* in a process, it starts by reading the status and *ID* of related CPO and finishes as soon as the object has a new status, e.g. an installation of prefabricated element starts when the state of this element changes from (be-stored) into (is-in-installing) and finishes as soon as the next element or next task has a new status then the predecessor element gets its final state (be-installed). It means, a task starts when one of the objects changes its status to execute this task. It finishes as soon as all related objects have new statuses and so forth. Consequently, a task status (i.e. start, in progress, finish, etc.) is defined by the states of it resources which are necessary to execute this task. Whereas, a state of a process can be seen as a combination of statuses of all its tasks and/or its sub-processes. The status concept can use for monitoring and progress measurements. Here, a continuous comparison of As-Planed against As-Is performance is used determine any deviation, conflicts or exceptions at run-time like delays in the ongoing process.

8 CONCLUSION

The work suggests a CPS concept for smoothly integrating the real physical construction entities into virtual information models based on semantic rules. A generic framework relies on CPS approach for the construction domain is introduced to accomplish the integration, close the information loop, and establish a bi-directional coordination between the cyber construction and the real field. The framework's design enables individual entities to work together in order to form complex systems with new capabilities.

The integration methods take into account the digital, spatial and physical construction objects. These methods allow construction object recognition and ensure a high functionality and collaboration and ultimate interoperability inside the system. Consequently, cyber-physical objects are embedded in the framework with a level of "smartness", including digital capabilities, context-aware content and specified behavior/ action. The site data capture method is based on a cost-effective passive RFID system convenient for tracking the physical entities. The content of captured data is leveraged by mapping the data capture system to semantic work zones. The geoSite concept simplifies the determination of site's work zones and makes the timely changes in their functionality tractable. It shifts a complex construction site into a set of functional oriented spaces.

Finally, the integration of the CPOs in construction process models supports deriving actual states of ongoing activities in order to track project progress. The analysis of actual against planned performance beyond the scope of this work can anticipate delays, errors or resources shortage during the construction phase. An application scenario for future work is to validate the process simulation model and improve simulation input data and reference process models with real parameters (Ismail, Srewil, and Scherer 2017). In addition, process control in a (semi-) automated manner using configuration templates technique can be used in order to offer alternative processes on time.

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