Improving supply chain communications for off-site construction using Process Specification Language

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Abstract –
Off-site construction has undergone a rapid development driven by their favorable characteristics, such as fast construction, waste reduction and clean on-site environment. Nevertheless, frequent engineering changes often create unpredictable challenges for precast production planning, resulting in production delay or additional storage costs. In order to achieve the target of just-in-time production and lean construction, it is vital to harmonize the supply chain communication amongst different phases of component production, transportation and on-site assembly. The automatic exchanges and conveyance of the process information amongst different phases are nearly impossible due to the mismatching definitions of semantics and syntax used in different planning software that are adopted in different construction phases, e.g. assembly design, component production, and on-site assembly. To address this problem, the Process Specification Language (PSL) is explored in this paper to unify the process information from multiple planning software applications. A translation framework of process information communications in the off-site construction supply chain has been developed based on the functional analysis. Semantic mapping and extensions of PSL are proposed, given the specific requirements of off-site construction scheduling management. Finally, the superiority of this method is demonstrated using two case studies to confirm the scheduling and sequencing information interaction amongst the phases of assembly design, component production, and on-site construction can be enhanced by the present method.

Keywords –
Process Specification Language; PSL; Supply Chain; Off-Site Construction; Process Ontology

1 Introduction

Compared to the traditional cast-in-situ construction methods, the successful management for off-site construction relies much more on the efficient precast supply chain management [1]. However, the supply chain management of off-site construction still faces many challenges, and the failure of just-in-time delivery of precast components is one of the most vital reasons for the delay on the construction site [2]. If the precast components arrive too early on the construction site, it will result in an increase in cost and on-site storage[3]. The off-site construction supply chain phases consist of planning, design, fabrication, delivery and on-site assembly. Frequent engineering alternations in the fabrication and construction phases, and the lack of or less effective coordination and communication, have made such problems more prominent. Improving the coordination and interoperability for various phases and parties, is considered to be the key to solve such issues in the off-site construction supply chain management [4].

The lack of ICT interoperability is primarily owing to the incompatibility amongst the syntaxes of the languages and the semantics of the terms [5] adopted in different phrases. To overcome this issue, one approach is to develop and update the different direct translators or core database adopted in different phases for each application, which lacks the required accuracy. The alternative approach is to develop a common data standard, e.g. IFC and EXPRESS. The NBIMS (National Building Information Modeling Standard) released the 'Information Delivery Manual for Precast Concrete' to further improve its support for data exchange during the life cycle of off-site construction projects [6]. At present, IFC standards can be used to communicate the product data and primary process data, but the necessary concepts and definitions to support more complex processes, e.g. the complicated scheduling and sequencing information are missing [7].

Construction supply chain management includes a set of process-driven activities. Precast fabricators usually apply ERP (Enterprise Resources Planning) system with MES (Manufacturing Execution System) and APS (Advanced Planning and Scheduling), to deal with the tasks of production scheduling, delivery planning and factory site storage. Contractors use the project management software to develop and control the assembly schedule on the project sites. The communication and coordination between the precast fabricators and contractors is based on delivery order, which is closely related to the progress of fabrication and construction. Thus, it brings up the question on how to achieve the information compatibility and interchangeability amongst the different software packages is of great practical relevance.

PSL ontology is considered as the process information interaction tool applied to the construction and supply chain management [8]. This paper incorporate the process information from different construction planning software and then apply the PSL ontology to strengthen the supply chain communications for off-site construction.

2 Literature Review

2.1 PSL Ontology

The concept of Ontology originated from the field of philosophy. Gruber defined it as 'an explicit specification of a conceptualization' [9]. To date, the research on ontology mostly focused on exploring how to describe a wide range of knowledge-sharing behaviors [10]. Ontology has a unified standard in the interpretation of knowledge items, suitable for data interoperability, information search and retrieval, automated inference and natural language processing in computer. Edward et al.[11] described a system to support multidisciplinary analyses of complex engineering problems by using pre-project planning ontology. Sheryl et al.[12] developed a feature ontology to support construction cost estimation by transforming the designer-focused product models into the estimator-focused product models.

Process Specification Language (PSL) is a set of logic terms to describe process which is applicable to manufacturing, engineering and business processes including production scheduling, process planning and management, business processes reengineering, simulation, realization, modeling and project management. ISO 18629provides the theoretical framework and application guides fpr PSL [13]. PSL contains 38 modules with more than 300 concepts in total. The core theory of the PSL ontology is illustrated in Figure 1 [14].

Cutting-Decelle et al. [15] illustrated the basic theorem of PSL and pointed out that PSL could be used for the representation and exchange of process information in Architectural Engineering and Construction (AEC) industry. PSL was proven to offer the interoperability improvement in the multiple process-related applications due to the function of formal semantic definitions and complete automization [16]. An ontology-based framework based on PSL was established, and the semantic presentation of design using PSL as well as the application in two case studies using CAD/CAM software were illustrated [17]. PSL was used to support the process information communication between multiple software including AutoCAD, Construction Computer Software and Microsoft project [18]. The main-stream methods and techniques to building supply chain communications were presented, including a new semantic-based approach [19]. PSL was used for information exchanges in a cross-disciplinary supply chain environment to describe the business process network and the information exchange of supply chain nodes amongst fabricators, suppliers and contractors [20].

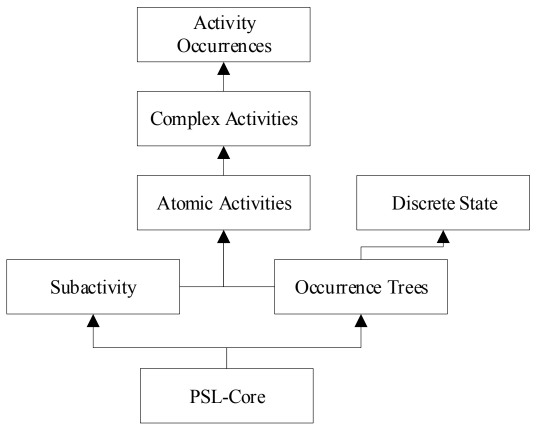

Figure 1. Core theory of the PSL ontology[12]

Cheng at al.[21] developed ontology mapping and information exchange amongst PSL, ifcXML and aecXML which can be applied in the project scheduling in the construction industries as the ontology standards. More studies have shown the ability of PSL in the information exchange of project scheduling among different software applications, e.g. Primavera P3, 4D Viewer Microsoft Project and Microsoft Excel [22]. Another study investigated how the PSL was used to indicate potential conflicts and to perform consistency checking on project scheduling information [23]. On this basis, a prototype framework enabling the remote collaboration of heterogeneous systems was proposed and a standard for data exchange based on PSL ontology was established [24]. A simulation access language (SimAL) based on PSL ontology was described to access and develop software applications for internet purposes[25]. A case study communicated online weather forecasting information with project scheduling and management application was illustrated to describe the use of the SimAL.

In summary, limited research has focused on the application of PSL ontology in AEC industry, which mainly targeted traditional on-site construction management. The instant interaction of process information is essential due to the tight connection of off-site production and on-site construction. Therefore, PSL ontology needs more research focused on its application, as it has the potential to bridge the gaps on the integration of off-site construction.

2.2 Knowledge Interchange Format (KIF)

KIF is a formal language designed to exchange knowledge among disparate computer systems, which is the grammar of PSL [26]. KIF was proposed and developed by the Logic Group of Stanford University and is a proposed draft American National Standard (pdANS).

KIF is based on the first-order logic and its language description includes syntactic and semantic standards. KIF supports declarative semantics, and the language is logically comprehensible [27]. KIF has two variants, i.e. the linear and structured KIFs. All expressions for linear KIF are ASC II strings, and the structured KIF includes characters, language elements, expressions and comments.

3 Process Information Communication in Supply Chain for Off-site Construction

3.1 Information Flow between Engineer, Precast Fabricator and Contractor

The supply chain of off-site construction contains a large array of parties including clients, architects/engineers, contractors, suppliers (precast fabricators) and consultants linked with comprehensive information flows [28]. In general, clients mainly take part in the planning and operation phases, and the consultants may not participate in the actual construction activities. The dynamic and constant communication of information amongst engineers, precast fabricators and contractors is vital for supply chain management during the whole construction processes. The information flowchart is presented in Figure 2.

Architects will pass the design model to engineers in the early stages based on the commencing order instructed by clients. The precast assembly drawings (PAD) made by engineers are then sent to precast fabricators and contractors simultaneously. On this basis, contractors can draw up the construction scheduling (CS), which will be subsequently sent to the precast fabricator. The precast fabricator can work out the production scheduling to meet the requirements of PAD and CS. The precast components will be produced in batches according to their specified delivery dates, and the contractor will use them for the construction assembly at sites.

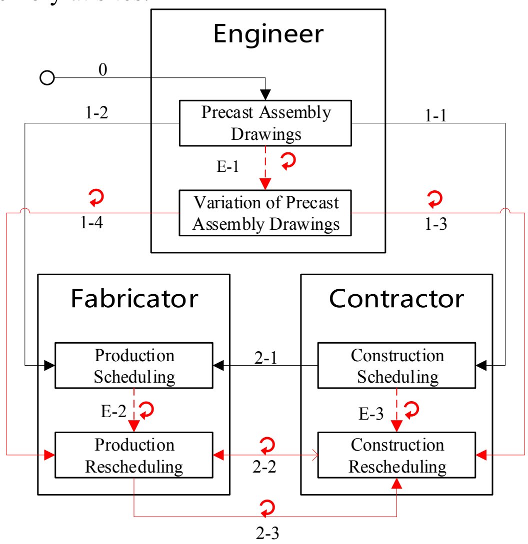

Figure 2. Typical information flow in supply chain

Table 1 Information Exchange and Type

Number	Information Exchange	Type
0	Start Order	Process
1-1	Building Information	Object
	Assembly Sequencing	Process
1-2	Component Design	Object
	Resource Require	O&P
	Assembly Sequencing	Process
2-1	Construction Scheduling	Process
1-3	Building Information Change	Object
	Assembly Sequencing Change	Process
1-4	Component Information Change	Object
	Resource Require Change	O&P
	Assembly Sequencing Change	Process
2-2	Construction Rescheduling	Process
2-3	Production Rescheduling	Process

A large number of engineering changes caused by unexpected situations occur frequently during the construction processes. The variation of PADs is required re-drawn by engineers when the architect modifies the design or the original design error is found and rectified (E-1). After the variation notification of precast design is sent to precast fabricators and contractors, the Production Rescheduling (PR) and Construction Rescheduling (CR) should be formulated accordingly. In addition, the production may also be triggered by the equipment failure or raw material supply delay (E-2). On the contractor side, some uncontrolled factors, such as weather conditions, construction machinery failure, may also lead to the necessity of PR (E-3). As a result, the precast fabricator may also develop PR based on the updated CR. Although these engineering changes occur on a random basis, it tends to occur frequently throughout the entire construction duration owing to the complexity of the construction environment. In summary, the type of the complicated information communication is listed in Table 1.

3.2 Applications by Software

The process information of supply chain can be divided into two types, i.e. business and construction information. Many different software packages can facilitate the construction management. For example, BIM-based software, such as Autodesk Revit, Tekla Structures, Nemetschek Allplan, Structure Works and IDAT CCAD, can support engineers to prepare precast assembly drawings. Precast fabricators use ERP (Enterprise Resource Planning) packages to manage the planning and scheduling of production, e.g. SAP ERP, IDAT ERP, Asprova APS and Nemetschek TIM. MES (Manufacturing Execution System) applications such as RIB SAA may also be adopted by precast fabricators to control machines for automatic production. Contractors often use Project management tools for on-site construction management, and the Microsoft Project, Oracle P6 and Autodesk Navisworks are widely adopted for such purpose. The typical software types used in different phases are shown in Figure 3.

Figure 3. Typical software used in different phases

3.3 Process Information Communication Using PSL Ontology

The process information communicate amongst different applications through syntactic and semantic translation. Figure 4 illustrates an example of data transferring between precast fabricator and contractor. The original files from IDAT ERP or MS Project can be transformed into their KIF syntax. And then they can be transformed into PSL ontology (KIF syntax and PSL terminology), where they can have some exchange. This process is reversible, through which the new data can be send back to their original applications in an opposite direction.

Although the ontology of the original application is usually hidden, users can create their own ontology based on the output from the application. The semantic translator unifies the terminology of each application with PSL definitions.

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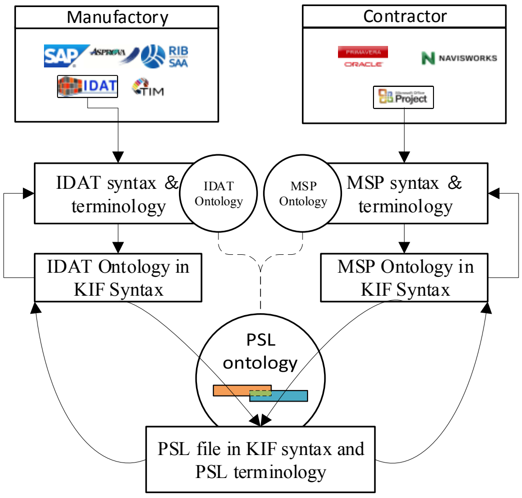

Figure 4. Process information exchange via PSL

4 Process Information Communication for Scheduling

The production scheduling of components needs to be synchronized with the on-site construction scheduling. However, the production and construction planning may be easily affected by the unpredictable factors on each side. In the current practice, the precast fabricator monitors the production anomalies and communicates with contractors on a weekly basis. The negative consequence as a result of this type of communication practice includes the sub-optimal decision-making, inadequate utilization of production capacity, and lagged feedback of information, which will lead to the failure of just-in-time delivery and lean construction. This will cause the delay in the overall project progress and the cost increase for both fabrication and construction. PSL ontology can be utilized to tackle this problem, namely, unify the production and construction scheduling via instant data transfer and synchronized communication. In doing so, the entire process information can be integrated into a single system and the scheduling can be automatically updated should any change in one of the process take place.

4.1 PSL Ontology Mapping for Construction Scheduling

MS Project and Oracle P6 are frequently used to perform construction scheduling in Construction management. Other software with the 4D management capabilities such as Naviswork also share the same principles and basic concepts as MS Project for scheduling management. Multiple concepts including tasks, duration, constraints, ordering relationship, order and resource requirement can be described with these applications. The logic of duration and ordering relationships can be expressed with Gantt chart, using different dependences relationships. The dependence elements include predecessors, successors, basic types and absolute/relative leading or lagging times, as shown in Figure 5, in which the relation between multiple process is also illustrated both in their full and abbreviated terms, e.g. Finish-to-Start and FS.

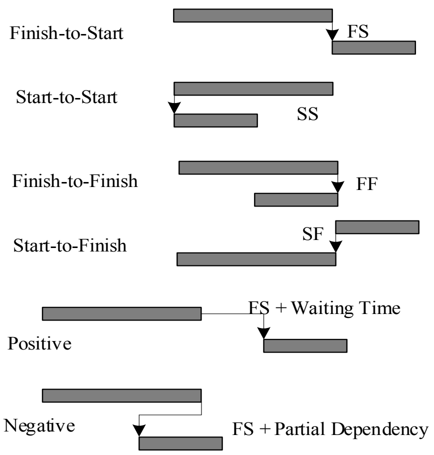

Figure 5. Construction Dependencies in Gantt Chart

Table 2 Semantic mapping of dependences relationship

Concepts in Project Management Apps	PSL terms
Predecessor/Successor	before-start, before-end, after-start, after-end
Finish-to-Start	meets, end-equal-start
Start-to-Start	starts, start-equal-start
Finish-to-Finish	finishes, end-equal-end
Start-to-Finish	start-equal-end
Positive Lag	before-start-delay, before-end-delay
Negative Lag	after-start-delay, after-end-delay

PSL ontology provides enough terms to represent the dependence relationship with the ordering relation extension and temporal ordering relations extension . A semantic mapping between dependences relationship and PSL ontology is listed in Table 2.

4.2 PSL Ontology Mapping For Production Scheduling

Two kinds of casting beds and casting flows exist in precast concrete plants, e.g. the mobile and fixed casting. The mobile casting method is more widely adopted owing to the higher level of mechanical automation and the efficiency in the space use. Hence, the mobile production mode is analyzed in this case study. The production scheduling can be shown by Production Gantt Chart as Figure 6 [29].

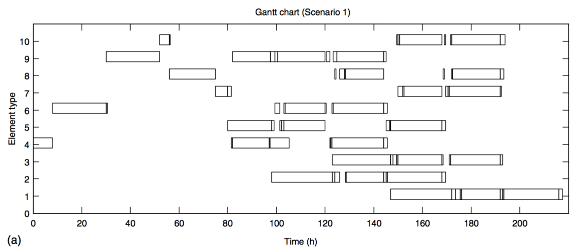

Figure 6. Production scheduling for Mobile Precast Concrete Casting [29]

In the streamline production mode, the semi-finished products may directly be sent into the back-end production line. The ordering relationships are more complicated than these in construction scheduling. Additional dependences relationships of SSFF, FSF and FFS are shown in Figure 7. For instance, SSFF means the start of the first production triggers, the start of the second and both lines will finish at the same time; FFS means that the second line will commence after a period of time following the first line, its predecessor, commences; FSF means that apart from the first round where the finishing of the first line triggers the starting of the second one, the remaining start of the first line will all depend on the finishing of the second line.

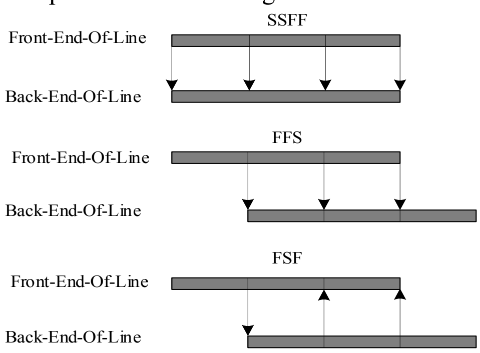

Figure 7. Production Dependencies in Gantt Chart

The relationship of SSFF, FSF and FFS can be described by PSL ontology as in Table 3.

Table 3 PSL term extensions for complex concepts

Concepts	PSL terms extensions
SSFF	*(defrelation SSFF (?a ?b) := (exists (?a1 ?a2 ?a3 ?a ?b1 ?b2 ?b3 ?b) (and (subactivity ?a1 ?a2 ?a3 ?a) (subactivity ?b1 ?b2 ?b3 ?b) (mutually-occurring ?a1 ?a2 ?a3 ?a) (starts ?a1 ?b1) (starts ?a2 ?b2) (starts ?a3 ?b3) (finishes ?a3 ?b3))))*
FFS	*(defrelation FFS (?a ?b) := (exists (?a1 ?a2 ?a3 ?a ?b1 ?b2 ?b3 ?b) (and (subactivity ?a1 ?a2 ?a3 ?a) (subactivity ?b1 ?b2 ?b3 ?b) (mutually-occurring ?a1 ?a2 ?a3 ?a) (meets ?a1 ?b1) (meets ?a2 ?b2) (meets ?a3 ?b3))))*
FSF	*(defrelation FSF (?a ?b) := (exists (?a1 ?a2 ?a3 ?a ?b1 ?b2 ?b3 ?b) (and (subactivity ?a1 ?a2 ?a3 ?a) (subactivity ?b1 ?b2 ?b3 ?b) (mutually-occurring ?b1 ?b2 ?b3 ?b) (meets ?a1 ?b1) (meets ?b1 ?a2) (meets ?b2 ?a3))))*

4.3 Example of Scheduling Communication using PSL Ontology

The information communication contains syntactic and semantic translation into the PSL ontology. The semantic translation is separately presented by PSL ontology mapping for construction scheduling and production scheduling. An example of information communication between MS Project and IDAT ERP software is introduced below.

It is a four-step work. Firstly, the MS Project data file is represented with PSL syntax and MS Project terminology, and then further written as a complete PSL representation. Next, these PSL representations are further transformed into PSL syntax and IDAT ERP terminology. Finally, the PSL syntax and IDAT ERP terminology is written as input file for IDAT ERP. The first two steps are shown below as an example， and the next two steps are the mirror work to the first two. This study takes an example to describe scheduling with multi dependences relationship in Figure 8.

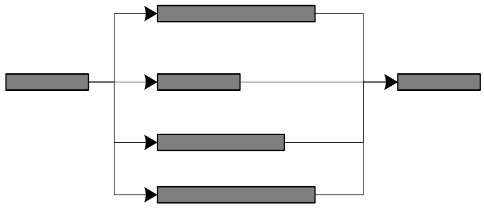

Figure 8. The example of multiple predecessors

The scheduling data written in MS Project using the VBA (Visual Basic for Applications) language, and the coding format and terminologies defined in VBA. The scheduling data file in MS project's representations is as below.

```
{Project        multiple Predecessors –opening (x)}
{Task           predecessor activity,
                intermediate activity group,
                successor activity}
{Dependence     order relationship as scheduling (x)}
{Period         duration as scheduling (x)}
```

For the translation process, a syntactic translator needs to be developed to read the scheduling file from MS Project. The syntactic translator then translates the original data to a presentation with PSL syntax and MS Project terminology as below.

```
(forall (?x)
(=>(multiple_predecessors-opening ?x)
    (task ?a ?b ?c)))
(forall (?b)
    (=>(and(activity_group ?b1 ?b2 ?b3 ?b)
    (StartToStart ?b1 ?b2 ?b3)
    (Period ?t1 ?t2 ?t3 ?b1 ?b2 ?b3))))
(forall (?occ)
(=>(and (ActualStartDriver ?a ?b ?c)
    (FinishToStart ?a ?b ?c)
    (Period ?t4 ?t5 ?t6 ?a ?b ?c)))
```

The PSL syntax can be mapped to PSL definitions. The presentation of the scheduling file adopts PSL ontology, which contains PSL terminology and PSL syntax as below.

```
(forall (?x)
(=>(multiple_predecessors-opening ?x)
    (activity ?a ?b ?c)
(forall(?b)
    (=>(and (subactivity ?b1 ?b2 ?b3 ?b)
        (starts ?b1 ?b2 ?b3)
        (=>(duration ?b1 ?t1))
        (=>(duration ?b2 ?t2))
        (=>(duration ?b3 ?t3)))))
(forall (?occ)
    (=>(and (occurrence_of ?a ?b ?c)
        (meets ?a ?b ?c)
        (=>(duration ?a ?t4))
        (=>(duration ?b ?t5))
        (=>(duration ?c ?t6)))))
```

5 Process Information Communication for Assembly Sequencing

BIM is usually adopted for virtual assembly analysis in addition to the complicated Precast Assembly Drawings. The assembly sequencing from virtual assembly analysis will be sent to precast fabricators and contractors. Process information of assembly sequencing is paramount between the communication of contractor and precast fabrication. The wrong assembly sequencing will result in project delays and additional costs for contractors. To the precast fabricators, the assembly sequencing will determine the stacking sequencing in transport vehicle and on-site yard. The correct stacking sequencing enables the crane to hoist the components directly one by one in order to save construction time and the storage space.

5.1 Example for Assembly Sequencing Process

The example project is a residential based on shear wall structure. The main structure consists of the precast shear walls, precast columns, laminated slabs and laminated beams. The BIM model build by Allplan is shown in Figure 9.

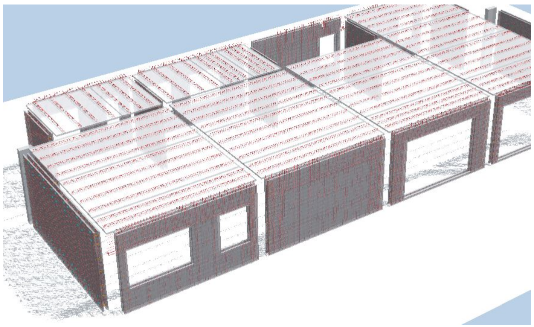

Figure 9. BIM model of the example project

Figure 10 illustrates the positions of precast components in the room at the corner, and the numbers have been assigned for each component. The entire assembly sequencing process of this room is described by IDEF3, as shown in Figure 11 and Figure 12. Figure 11 shows the main activities of the whole assembly process. The precast shear wall and the precast column must first be assembled before the laminated beam is assembled. Figure 12 illustrates the sub-activities of shear wall assembly. The inner wall (S3) and the wall on the other side from crane (S1&S2) will be first assembled. The outer wall and the wall near the crane will be finally assembled to insure the hoisting space.

5.2 Assembly Sequencing Process by PSL Ontology

In order to describe the assembly sequencing process, the PSL ontology is used to translate the activities as indicated in Figure 11.

(subactivity assemble-shear-wall)
(subactivity assemble-column)
(subactivity assemble-beam)
(forall (?occ))
(<=>(occurrence_of ?occ assemble-room1)
(exsits (?occ1 ?occ2 ?occ3)
(and (occurrence_of ?occ1 assemble-shear-wall)
(occurrence_of ?occ2 aseemble-column)
(occurrence_of occ3 assemble-beam)
(subactivity_occurrence ?occ1 ?occ)
(subactivity_occurrence ?occ2 ?occ)
(subactivity_occurrence ?occ3 ?occ)
(soo-precedes (soomap ?occ1)(soomap ?occ 3) assemble-room1)
(soo-precedes (soomap ?occ2)(soomap ?occ3) assemble-room1)
(strong_parallel ?occ1 ?occ2 assemble-room1))))))

6 Conclusion and Future Work

This paper presented the novel method of PSL ontology to improve the supply chain communications for off-site construction. PSL ontology has rich definitions to describe process activities in scheduling and sequencing. It can be used to provide a common framework to exchange data originated from different application packages used in various construction phases. While IFC provides the fundamental data structure of BIM applications, PSL has the potential to be incorporated with IFC so that the supply chain communication for off-site construction can be integrated into both domains of the building information and construction activities.

7 Acknowledgement

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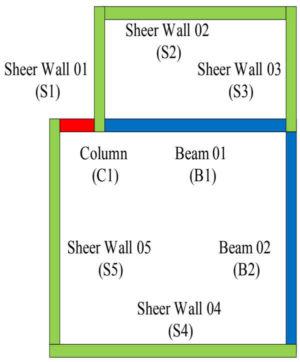

Figure 10. The components position in the room at corner

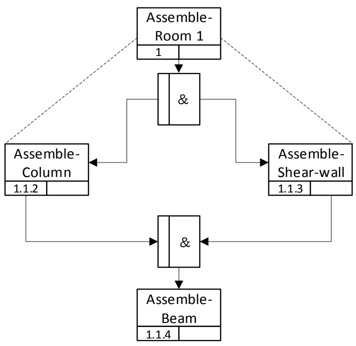

Figure 11. Main activities of the whole assembly process in IDEF3

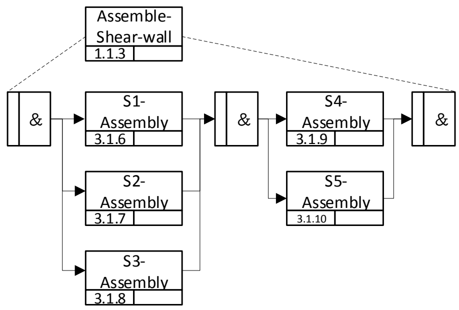

Figure 12. Sub-activities of the shear wall assembly process in IDEF3

References

[1] Tatum, C. B., Vanegas, J. A. & Williams, J. M.Constructability Improvement Using Prefabrication, Preassembly, and Modularization. Bureau of Justice Statistics, 1986.

[2] Wang Z., Hu H. & Gong J. Framework for modeling operational uncertainty to optimize offsite production scheduling of precast components. Automation in Construction, 86: 69-80, 2018.

[3] Marasini, R., & Dawood, N. Simulation modeling and optimization of stockyard layouts for precast concrete products. Simulation Conference, IEEE: Proceedings of the Winter, 1731-1736, 2002.

[4] Cheng, C. P., Law, K., & Bjornsson, H. A Distributed Portal-Based Platform for Engineering & Construction Supply Chain Interoperability. CIFE Technical report# TR173, Centre for Integrated Facility Engineering, Stanford University, 2008.

[5] O'Brien, W. J., Formoso, C. T., Vrijhoef, R., & London, K. A. Construction supply chain management handbook. Construction Management & Economics, 27(27), 1265-1266, 2008.

[6] Eastman, C., Sacks, R., Panushev, I., Aram, V., & Yagmur, E. Information delivery manual for precast concrete. PCI-Charles Pankow Foundation. http://dcom.arch.gatech.edu/pcibim/documents/ID M_for_Precast. pdf (last accessed on 6/20/2010), 2009.

[7] Cheng, J. A simulation access language and framework with applications to project management (Doctoral dissertation, Stanford University), 2004.

[8] Cutting-Decelle, A. F., Young, B. I., Das, B. P., Case, K., Rahimifard, S., Anumba, C. J., & Bouchlaghem, D. M. A review of approaches to supply chain communications: from manufacturing to construction. Journal of Information Technology in Construction (ITcon), 12(5), 73-102, 2007.

[9] Gruber, T. R. A translation approach to portable ontology specifications. *Knowledge Acquisition*, 5(2), 199-220, 1993.

[10] Fikes, R., Cutkosky, M., Gruber, T., & Van Baalen, J. Knowledge sharing technology project overview. Technical Report KSL 91-71, Stanford University, Knowledge Systems Laboratory, 1991.

[11] Divita, Edward L., John C. Kunz, & Martin A. Fischer. Collaborative desktop engineering. Artificial Intelligence in Structural Engineering. Springer, Berlin, Heidelberg, 69-85, 1998.

[12] Staub–french S, Fischer M, & Kunz J. A feature ontology to support construction cost estimating. AI EDAM, 17(2): 133-154, 2003.

[13] Pouchard, L. C., Cutting-Decelle, A. F., & Grüninger, M. Iso 18629 psl : a standardised language for specifying and exchanging process information. *IFAC Proceedings* Volumes, 38(1), 37-45, 2005.

[14] ISO 18629-13:2006, Industrial automation systems and integration - Process specification language.

[15] Cutting-Decelle, A. F., Anumba, C. J., Baldwin, A. N., Bouchlaghem, N. M., & Tesfagaber, G. PSL: a common language for the representation and exchange of process information in construction. In *1st International Conference on Innovation in AEC*, CICE, University of Loughborough, UK, 2001.

[16] Tesfagaber, G., Anumba, C. J., Bouchlaghem, N. M., Baldwin, A. N., & Cutting-Decelle, A. F. (2003). Semantic Process Modeling for Applications Integration in AEC. *In Computing in Civil Engineering* (pp. 318-335), 2002.

[17] Cutting-Decelle, A. F., Young, R. I., Anumba, C. J., Baldwin, A. N., & Bouchlaghem, N. M. The application of PSL to product design across construction and manufacturing. *Concurrent Engineering*, 11(1), 65-75, 2003.

[18] Tesfagaber, G., & Bouchlaghem, N. M. Automation of process information exchange between AEC software applications using PSL. International Journal of IT in Architecture, Engineering and Construction, 2(4), 315-332, 2004.

[19] Cutting-Decelle, A. F., Das, B. P., Young, R. I. M., Case, K., Rahimifard, S., & Bouchlaghem, N. M. Building supply chain communication systems: a review of methods and techniques. Data science journal, 5: 29-51, 2006.

[20] Cutting-Decelle, A. F., Young, R. I. M., Case, K., Rahimifard, S., & Anumba, C. J., et al. Towards the understanding of the requirements of a communication language to support process interoperation in cross-disciplinary supply chains. *International Journal of Computer Integrated Manufacturing*, 20(4), 396-410, 2007

[21] Cheng, J., Trivedi, P., & Law, K. H. Ontology mapping between PSL and XML-based standards for project scheduling. *In international conference on concurrent engineering in construction*, 2002.

[22] Cheng, J., Law, K. H., & Kumar, B. Integrating project management applications as web services. *In Proceedings of the 2nd international conference on innovation in architecture, engineering and construction* (pp. 25-27), 2003

[23] Cheng, J., Gruninger, M., Sriram, R. D., & Law, K. H. Process specification language for project scheduling information exchange. I*nternational Journal of IT in Architecture, Engineering and Construction* (pp.4--307), 2003.

[24] Cheng, J., Law, K. H., & Kumar, B. Online collaboration of Project management applications. *In Proceedings of the 11th International Workshop*

of the EG-ICE, 2004.
[25] Cheng, J., Lau, G., & Law, K. A simulation access language and framework for project management applications, 2004.
[26] Genesereth, M. R., & Fikes, R. E. Knowledge interchange format-version 3.0: reference manual, 1992.
[27] Genesereth, M. R. Knowledge Interchange Format draft proposed American National Standard (dpANS) NCITS. T2/98-004,1998.
[28] Al-Bazi, A., & Dawood, N.Improving performance and the reliability of off-site pre-cast concrete production operations using simulation optimisation. *Experimental Cell Research*, 278(2), 146-157, 2010.
[29] Wang, Z., & Hu, H. Improved precast production scheduling model considering the whole supply chain. *Journal of Computing in Civil Engineering*, 31(4), 2017.