Realizing, Twinning, and Applying IFC-based 4D Construction Management Information Model of Prefabricated Buildings

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Abstract –

Prefabrication is regarded as the first level of industrialization in the construction industry. A unified 4D information model with good interoperability is the key issue to realize effective project management of prefabricated buildings. This paper intends to promote prefabricated buildings' management by developing an IFC-based framework to institute a unified 4D information model and realize its interoperability in Graph Database. The framework consists of three parts. The first part is to realize a unified IFC-based 4D construction management information model of prefabricated buildings. The prefabricated building information model is extended based on the IFC schema, including the extension of schedule information, resource information, and cost information. The second part is twinning the obtained information model into a graph database via Neo4j. The third part consists of strategies to interoperate, verify, and visualize the IFC-based information model based on the graph database. A prefabricated engineering case verifies that the proposed framework's feasibility. This framework can be extended to the nD and lays the foundation of IFC-based digital twin and thus could favorably contribute to the development of prefabricated buildings.

Keywords –

IFC standard; prefabricated buildings; construction management information; graph database

1 Introduction

In recent years, prefabricated buildings have attracted more attention in civil engineering due to their characteristics of low pollution, low cost, and high industrialization [1]. However, prefabricated buildings have not rapidly developed as expected.

Researches show that information sharing among the whole participants and process is one of the most influential critical success factors required for construction management of prefabricated buildings [2,3]. The BIM platform aims to promote information sharing between stakeholders at different construction project stages to make better decisions [4]. Limited by the current barriers of information interoperation in different BIM software, the 4D construction management information of prefabricated buildings cannot be well transmitted to all disciplines, participants, and the whole construction cycle. As the primary data standard of BIM, the IFC (Industry Foundation Classes) standard developed by buildingSMART plays a significant role in the process of describing building information since it is mainly serving as a global standard for BIM data exchange[5]. Therefore, a unified construction management information model can be established using the IFC standard, thus promoting the management of prefabricated buildings.

Although the IFC standard is widely applied in various scenarios, it still has obvious shortcomings. Firstly, there is no extension of prefabricated buildings' construction management in the current IFC schema, making it challenging to share completed construction management information [6]. Secondly, most data mining techniques lack the capability to handle IFC directly[7]. Further, there is a lack of efficient strategies to use IFC as the data foundation of digital twin[8]. Therefore, this paper intends to promote prefabricated buildings' management by developing an IFC-based framework to institute a unified 4D information model and realize its interoperability in Graph Database. The framework consists of three parts. The first part is to realize a unified IFC-based 4D construction management information model of prefabricated buildings. The second part is to twin the obtained information model into a graph database via Neo4j. The third part consists of strategies to interoperate, verify and visualize the IFC-based information model based on the graph database.

This framework will be the foundation of any researches about the IFC-based information model's analysis.

2 Literature Review

2.1 4D BIM in construction management

The 4D BIM construction technology increases the dimension of time based on the 3D model[9] so that the entire construction process can be expressed dynamically and thus more intuitive. The 4D theory was first proposed by Stanford University in 1996, and the CIFE 4D-CAD system was developed on this basis[10]. Jianping Zhang's team proposed an extended 4D construction management model[11]. This model takes WBS as the core and combines construction management elements such as schedule planning and resource management to visualize the construction process. In 2012, a 4D Site Management Model (4DSMM)[12] was further proposed by this team. 4DSMM links 3D models with specific schedules to generate 4D models of site management. Additionally, De Soto[13] also used a tabu-search algorithm and 4D models to improve the construction project schedule.

Albeit using 4D BIM in the management of prefabricated buildings can benefit a lot, 4D BIM cannot be cultivated with incomplete, untimely data exchange and lacking real-time visibility[14]. Firstly, forming the 4D BIM models relies on specific BIM software, which means information cannot interoperate with other BIM software once separate from this particular software. Moreover, information from a single BIM model is insufficient to meet construction management[15]. However, there is no effective information transfer mechanism between different BIM models. In summary, the lack of information exchange between BIM software keeps the management of prefabricated buildings inefficient and locked-in to tool vendors[16]. This paper intends to adopt the standard for sharing data in the whole process of engineering projects - IFC standard - as the basis for modeling the 4D management information model of prefabricated building.

2.2 IFC Standard

The IFC standard has been widely studied and applied worldwide once it was launched. Many scholars extended the IFC standard in terms of construction management information. Jongcheol Seo[17] proposed an IFC extended model that can store plan information. Akinci[18] proposed extending the IFC framework and integrating the project model of completion and design information to achieve automatic completion conditions assessment. Nevertheless, reviewing the existing literature, there is no method to extend the IFC standard to the construction management information of prefabricated buildings.

Meanwhile, the extension model based on IFC standards can seldom be verified on the appropriate software. The functions and characteristics of common IFC software are shown in **Table 1**. For example, common 3D BIM software such as XbimXplore can perform an excellent 3D display of IFC files, but they do not support 4D display of the construction process.

Table1. Software for parsing IFC files and their features

Functions	Software	Features
IFC files parsing	xBIM	It can generate IFC files.
	IFC-gen	It can automatically generate syntax trees.
	IfcEditor	It can parse text and generate syntax trees.
	IFC File Analyzer	It can generate xls files.
	IfcOpenShell	It supports Python to compile IFC files.
IFC models display	BIM Vision	1. Can display 3D models. 2. Support the parsing of most IFC entities, except IfcTask and IfcTaskTime.
	Solibri Anywhere	
	XbimXplore	
	IFC++	

2.3 Database Technology's Applying in the IFC Information Model's Storage

As mentioned before, IFC information model stored as pure text is hard to be applied directly. Hence, database technology is chosen to store IFC. Researches have tried to use a relational database to store IFC information models. Solihin[19] transformed BIM data into an open relational database to make the BIM data accessible for wide ranges of query capabilities. Marmo[20] mapped the IFC schema into a relational database to support performance assessment and maintenance management. However, using a relational database to store IFC requires creating extremely complex data tables and a lot of time-consuming cross-table joins to perform various complex queries. Meanwhile, other researchers verified the NoSQL database's advantages in query speed and flexibility. Beetz[21] developed an open-source BIM server based on BerkeleyDB, which provides incremental model storage, extraction, and conversion functions. Lin[22] realized IFC's storing for path planning based on MongoDB. Ma et al. [23] developed a Web-based BIM collaboration based on MongoDB. This framework will adopt a more intuitive non-relational database – graph database to store IFC information models. The detailed description of the graph database will be seen in Section 3.2.

3 Proposed Framework

This paper intends to promote prefabricated buildings' management by developing an IFC-based framework to institute a unified 4D information model and realize its interoperability in Graph Database. The proposed framework is shown in **Fig.1.** The framework is divided into three parts, namely, establishing, twinning, and applying the IFC-based 4D construction management information model of prefabricated building.

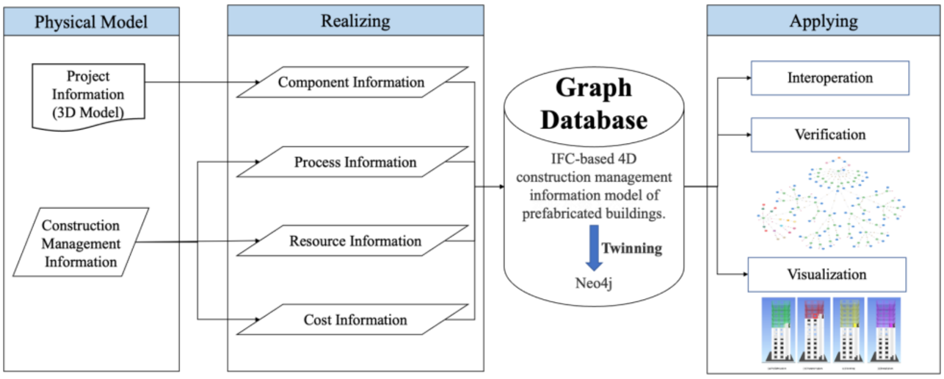

Fig.1 Proposed Framework

3.1 Establishing the IFC-based 4D construction management information model of prefabricated buildings

This framework proposed a unified method to realize an IFC-based 4D construction management information model of prefabricated buildings. The establishment of an IFC-based 4D construction management information model is divided into two steps. The first step is to extend the IFC schema by creating the template of the IFC-based 4D construction management information model. The second step is to instantiate the template one by one according to the obtained construction information.

3.1.1 Realizing process information's extension based on IFC standard

Firstly, this framework realizes process information's extension based on IFC standard. In the IFC standard, the entity *IfcProcess*, its subtypes and the corresponding relationship entities are used to describe the project's process. *IfcTask* is used to describe specific tasks in the construction process, and the entity *IfcRelSequence* is used to describe the sequence of these tasks. Furthermore, *IfcTask* can establish a hierarchical relationship with each other through the entity *IfcRelNests*.

Secondly, this framework realizes resources information's extension based on IFC standard. In the IFC standard, the entity *IfcResource* and its subtype *IfcConstructionResource* are used to describe resource information. Similarly, this framework realizes cost information's extension based on IFC standard. In the IFC standard, the entity *IfcCostItem* is used to describe the cost items. With entities *IfcRelAssociates-AppliedValue*, *IfcAppliedValue*, *IfcCostVaule*, and *IfcAppliedValueRelationship* to describe the algorithmic association between cost and value. Therefore, the cost information of the IFC information model can be formed.

Finally, this model takes the *IfcTask* as its mainline and relates with the relevant components, resource information, and cost information. Specifically, *IfcRelAssignsToProduct* associates *IfcTask* with the components related to the construction process, and the relationship entity *IfcRelAssignsToProcess* associates *IfcTask* with the resource information and cost information related to the construction process. **Fig.2** illustrates the complete template of the construction information model based on the IFC standard.

3.1.2 Instantiating the IFC-based 4D construction management information model of prefabricated buildings

This part will use the xBIM Nuget package under the Visual Studio platform to instantiate the IFC-based 4D construction management information model of prefabricated buildings.

Through the instantiation of process, resource and cost information of prefabricated buildings, a complete IFC-based 4D construction management information model of prefabricated buildings is formed eventually. The prefabricated building construction process is divided into components' prefabrication, transportation, hoisting, and installation in the information model. Therefore, these four parts correspond to four summary job tasks and further subdivide these four summary job tasks according to the types of components. The summary task TaskFabricate Summary is subdivided into prefabricating slabs, walls, roofs and other components.

Then the summary tasks at this level are subdivided into tasks corresponding to specific components. The rest of the summary tasks and specific tasks can be deduced by analogy. Finally, each specific task is associated with process information, resource information, and cost information, and forming a complete IFC-based 4D construction information model of prefabricated buildings.

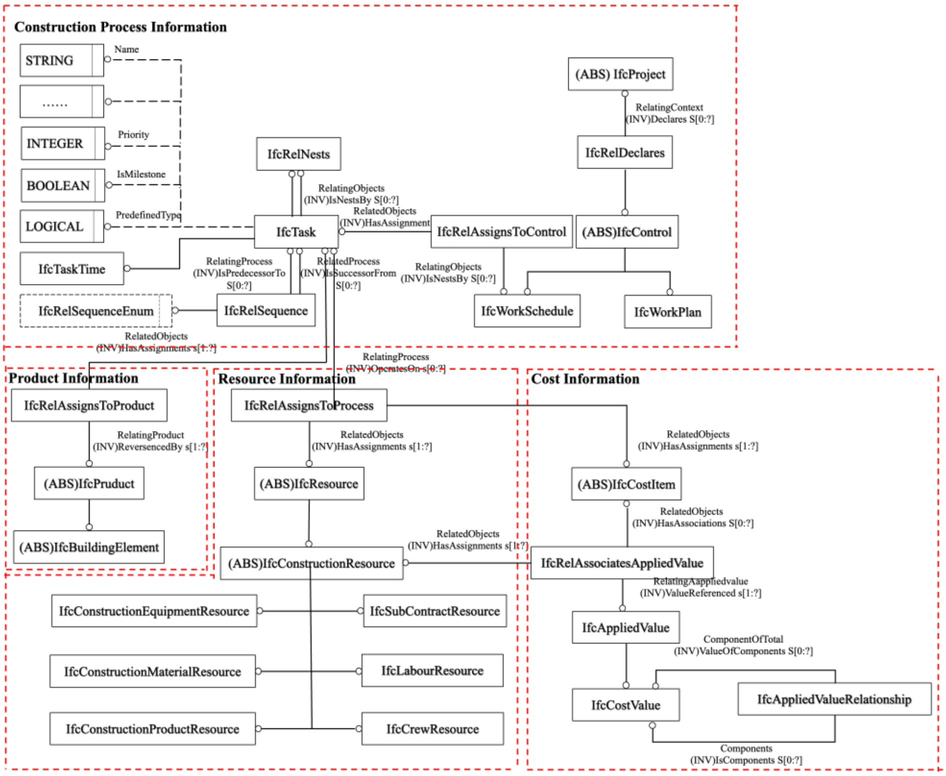

Fig.2 IFC-based construction management information model's template

3.2 Twinning the IFC-based 4D construction management information model into Neo4j

Furthermore, this framework twins the obtained IFC-based 4D construction management information model into a graph database Neo4j. One feature of the IFC Standard is that the reference relationship between the entities in the IFC-based information model is complicated, leading to the poor readability of the IFC files. Meanwhile, the IFC files obtained in the previous step are hard to modify, update, and interoperate. In sum, IFC information models are insufficient in digital interoperation. Thus, an automatic algorithm to parse and twin IFC files is necessary to reveal the IFC files' complicated inner relationships in an intuitive graph and increase data interoperability for further management requests.

The reasons to use Graph Database to store and twin the IFC-based information model are as follows. Firstly, according to the literature review, the non-relational database is more suitable than the relational database to store IFC information models. Secondly, the Graph Database is more suitable than other non-relational databases. IFC files and Graph Database have the same graph format. The reference relationship between entities in the IFC files is analyzed and shown in **Fig.3**. These entities' relationship is very similar to the relationship between nodes in a graph database, as illustrated in **Fig.4**. A graph database can be seen as a combination of nodes and relationships. And the graph database stores data in nodes with attribute values and uses relationships to organize these nodes, which are all consistent with IFC files' characteristics. Therefore, using Graph Database to store IFC files is more intuitive than other NOSQL databases.

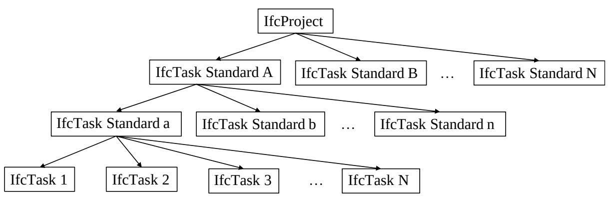

Fig.3 Entities reference relationship in an IFC file

Fig.4 Graph database [24]

Therefore, it is feasible and reasonable to adopt the graph database to store and twin the IFC-based information model. All the procedures are realized in Neo4j, which is a popular Java-based Graph Database. This paper will twin the IFC information model into the graph database via Java. The process is divided into the following six steps.

Step1. Using IFC Java Tool Box to parse IFC files. The IFC Java Tool Box consists of three main parts: obtaining the Java class by parsing the IFC entity type, obtaining the Java type by parsing the IFC data content, and providing the object model IfcModel for IFC data to access.

Step 2. Based on IFC schema, constructing a dictionary of the IFC entities and its key/value is corresponding to IFC entities' attributes;

Step 3. Specify the database path and create an EmbeddedGraphDatabse instance under the path;

Step 4. Generate the Node instance corresponding to the IFC entity through the designed createNode() method, and the information in the IFC entity is stored in the node's properties through the key-value set by the dictionary;

Step 5. Create the relationship between nodes, which is the relationship between IFC entities, through the designed createRelationship() method.

Step 6. Accessing the graph database using Cypher command.

Therefore, an automatic algorithm to twin the IFC-based 4D construction information model to the Neo4j graph database is realized and the database can be used as a platform for participants to interoperate the construction information.

3.3 Applying the IFC-based 4D construction management information model of prefabricated buildings in Graph Database

3.3.1 Interoperation of the IFC-based Graph Database

The ability to interoperate the construction information in real-time is the most significant advantage of twinning the IFC information model into the graph database. The process of data interoperating is simple. Through uploading the Graph Database to the cloud, the participants in the process of prefabrication, transportation, hoisting, and installation can interoperate on-site data to the database. Further, the construction data obtained by vision-based construction process sensing[25] can also be updated into the database. This process will be much easier than interoperate with the IFC files.

3.3.2 Verification of the IFC-based Graph Database

Through this form of a graph, the users can clearly understand the inter-related relationship between entities, as well as the hierarchical relationship of the entire information model. Benefitting from the graph database's intuitive relationship, users can also get other information directly related to the construction information. For example, a user searches for a construction task and returns an IfcTask node, as well as the IfcResouce, IfcCostItem, and IfcProduct nodes that are directly associated with the IfcTask. Accordingly, the correctness of the extension is verified. Specifically, whether the extensions of the relevant entities are completed and whether the associations between entities are correct can be visually verified.

3.3.3 4D display of the IFC-based Graph Database

As for the prefabricated buildings, what users are most concerned about is the state of the components in a prefabricated building over time, as well as information about the resources and cost associated with them. This section proposed a method to display a process model extracting from the IFC-based and graph database-based information model in 4D effect.

In this section, MS Project 2013 and Navisworks 2019 are used to visualize the information model. Project and Navisworks are the most commonly used management software in building construction, but they don't support the IFC format well. It makes the use of construction management information very inefficient and inconvenient. The specific implementation process is as follows. Initially, all the IfcTask entities in the created IFC-based graph database are obtained automatically through programming. Next, these IfcTask entities' properties are written into the Microsoft Project software. The same method is used to extract the information in IfcCostItem entities to obtain the cost corresponding to each IfcTask entity. Finally, importing the Revit building model and MS Project data into Navisworks simultaneously to achieve the 4D display of construction information management.

4 Case Study

The engineering case selected is a high-rise affordable housing project located in Shanghai, China, with a total construction area of 32,500 square meters, and the main building has 13 floors. The simplified model is illustrated in **Fig.5**.

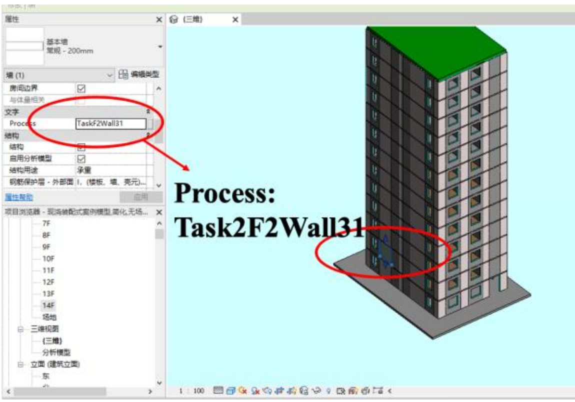

Fig.5 The simplified building's Revit model

4.1 Realization of IFC-based 4D construction management information model of engineering case's prefabricated building

According to the framework proposed in this paper, an IFC-based 4D construction management information model of this case study's prefabricated building is established.

The central part of this created IFC-based 4D construction management information model is shown in **Fig.6**. In this IFC model, the project (#1) has a general construction task named TaskGroundLevel(#1036), which is composed of 1-13 floor's construction tasks(#1039-#1063). Every floor's construction task includes four summary tasks: fabrication's summary task (#1065), transportation's summary task (#1091), hoisting's summary task (#1171), and installation's summary task (#1143). Furthermore, taking fabrication's summary task as an example, fabrication's summary tasks nested by slab fabrication's summary task (#1067), slab fabrication's summary task (#1072), and roof fabrication's summary task (#1085). The slab fabrication's summary task is composed of tasks corresponding to specific components (#1067). Meanwhile, for each task of a specific component, the process information, resource information, and cost information related to the task are established in the information model. Taking the fabricate task of the 1st-floor slab as an example (#1067), the process information, labor resource information (#1247), material resource information (#1248), equipment resource information (#1249), and cost information (#1253-#1255) as well as the slab (#200) corresponding to the task are associated to it.

```
#1=IFCPROJECT('12bxz3uTDC4wb_jB5gE948','OwnerHistory',$
,$,$,'I:\\Revit\\House1.ifc',$,$,$);
#1036=IFCTASK('1zkqn2e7LFhg2St02HQTwu',#1027,'TaskGrou
ndLevel',$,$,$,$,$,$,.F.,$,#1035,$);
#1039=IFCTASK('0NP1O_S$r8$eViUO4glyKt',#1027,'TaskGrou
ndLevel1',$,$,$,$,$,$,.F.,$,#1038,$);
#1065=IFCTASK('011WcvxnbD8AZVZ2Q7dd8W',#1027,'TaskF
abricateSummary',$,$,$,$,$,$,.F.,$,#1064,$);
#1067=IFCTASK('3MOUWoiRz2NuBJwJ2nJfbV',#1027,'TaskFa
bricateSlabSummary',$,$,$,$,$,$,.F.,$,#1066,$);
#1069=IFCTASK('0nOmrtxyj2VBWkHO5P4SnH',#1027,'TaskFa
bricateSlab1',$,$,$,$,$,$,.F.,$,#1068,$);
#1091=IFCTASK('0huWK9JJr4rfdG4_i4MQap',#1027,'TaskTrans
portSummary',$,$,$,$,$,$,.F.,$,#1090,$);
#1117=IFCTASK('1Ys2i9e8nBYvzKk8O1wo7s',#1027,'TaskHois
tSummary',$,$,$,S,$,$,.F.,$,#1116,$);
#1143=IFCTASK('3RNsuY0gH56g4d3ZNj65hy',#1027,'TaskInsta
llSummary',$,$,$,$,$,$,.F.,$,#1142,$);
#1168=IFCRELNESTS('2FNkC4Z8bEmPoiDAwKYBkT',#1027,$
,$,#1036,(#1039));
#1240=IFCRELSEQUENCE('3uhXQNRNb9sAZ8jEi5vq58',#102
7,$,$,#1161,#1166,$,.START_START.,$);
#1247=IFCLABORRESOURCE('2ZPqsrMRD0uehic7XAYwTb',
#1027,'LaborResourceHoistSlab1',$,$,$,$,$,$,$,.CONCRETE.);
#1248=IFCCONSTRUCTIONMATERIALRESOURCE('1N5hK
Wta53cuWxoopADUpr',#1027,'MaterialResourceHoistSlab1',$,$,$
,$,$,$,#1243,.CONCRETE.);
#1249=IFCCONSTRUCTIONEQUIPMENTRESOURCE('0fUvY
Jc5jCKPeiVBfqPWIV',#1027,'
EquipmentResourceHoistSlab1',$,$,$,$,$,$,$,.TRANSPORTING.)
#1253=IFCCOSTITEM('1CZAhyPqD3hAzaDo_GSMhV',#1027,'
LaborCostItemHoistSLab1',$,$,$,$,(#1250),$);
#1256=IFCRELASSIGNSTOPROCESS('0pSmSJ3qD3vOKmPB
OgvRTN',#1027,$,$,(#1247,#1248,#1249,#1253,#1254,#1255),$,#
1121,$)
```

Fig.6 Selected IFC file

4.2 Twinning the IFC-based 4D construction management information model of engineering case's prefabricated building

The IFC-based 4D construction management information model of engineering case's prefabricated building is twinning into Neo4j Graph Database. From **Fig.7**, we can conspicuous detect that *IfcTask* is divided into four levels. The first layer is the summary construction tasks for each floor, which are all associated with the *IfcWorkSchedule* entity representing each floor's general schedule. The second layer is the four summary tasks of prefabrication, transportation, hoisting, and installation. The third layer is the next layer's summary tasks, which means the fabricate task is divided into three summary tasks: slab fabrication, wall fabrication, and roof fabrication. The fourth layer is the specific tasks. For example, the fabrication of walls is divided into the fabrication of No. 1, No. 2, No. 3, and No. 4 walls, and the rest of the specific tasks are analogized. Therefore, through the IFC information model's storage and analysis by the graph database, the relationship between entities in the IFC information model can be read and analyzed intuitively.

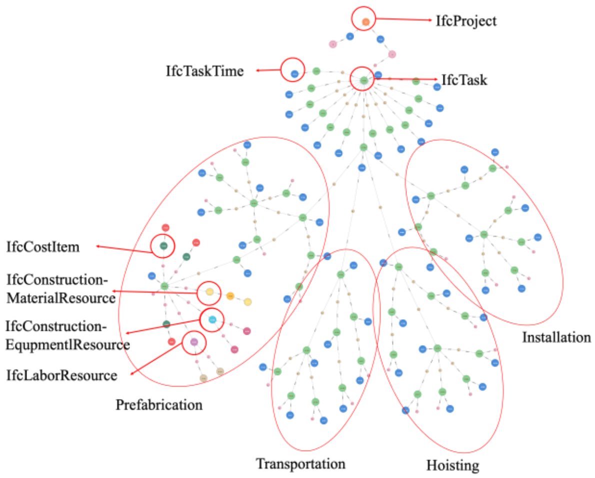

Fig.7 Information model's verification

4.3 Applying the IFC-based 4D construction management information model of prefabricated buildings in Graph Database

The interoperation of participants and Neo4j database will be performed throughout. In the stage of schedule plan, the Graph Database will be imported into a discrete event simulation model, established by using CBS(constraint based simulation) method [26], and the output schedule plan will be updated into the database. When it comes to the actual construction phase, the construction data obtained by advanced technologies such as vision-based automatic progress monitoring[27] will also be updated into the database. Therefore, the information sharing among the whole construction management stages is realized.

The correctness of the extension and entities' interrelationship can be easily verified in **Fig.7**.

The 4D display of IFC-based 4D construction management information model is executed as follows. First, the process model is extracted from the IFC-based and graph database-based 4D construction management information model. **Fig.8** is the demonstration of this step's effect. Then, importing the Revit building model and Project data into Navisoworks simultaneously to achieve the 4D display of construction information management. The screenshot of the animation is illustrated in **Fig.9**. To distinguish different stages in the process of dynamic display, this paper divides the construction process of the prefabricated building into four stages: prefabrication, transportation, hoisting, and installation. In the displayed animation, the four stages can be marked with different colors so that the entire construction process looks more intuitive and vivid.

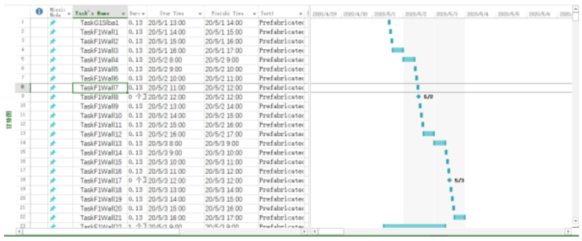

Fig.8 Importing process information into Project

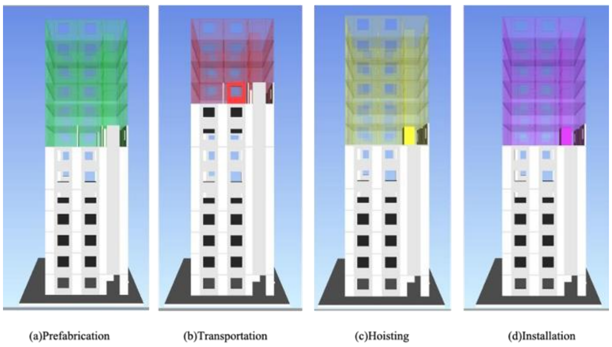

Fig.9 Screenshot of animation in Navisworks

5 Conclusion

In conclusion, the proposed framework is validated through the case study. It is illustrated that this framework successfully realizes an IFC-based 4D construction management information model of prefabricated buildings and twins it into Graph Database which can be applied to interoperate, verify, and visualize this construction management information model. Shortly, the significance of this paper is to innovatively propose an IFC-based and graph data-based information model to solve the difficulties of ineffective data interoperation in prefabricated buildings' construction management. In the future, this framework can be extended to the nD and becomes the standard process to extend the users' needed information during the construction management. Further, this framework's IFC-based Graph Database can be the digital foundation of advanced smart construction services, such as digital twin.

References

[1] Y. Ji, K. Qi, Y. Qi, Y. Li, H.X. Li, Z. Lei, Y. Liu, BIM-based life-cycle environmental assessment of prefabricated buildings, *Eng. Constr. Archit.*

Manag., 27 (8):1703-1725, 2020.

[2] W.M. Alruqi, M.R. Hallowell, Critical Success Factors for Construction Safety: Review and Meta-Analysis of Safety Leading Indicators, *J. Constr. Eng. Manag.* 145 (3):04019005, 2019.

[3] K. Shoieb, M.H. Serror, M. Marzouk, Web-Based Tool for Interoperability among Structural Analysis Applications, *J. Constr. Eng. Manag.*, 146(6):04020058, 2020.

[4] D. Bryde, M. Broquetas, J.M. Volm, The project benefits of Building Information Modelling (BIM), *Int. J. Proj. Manag.*, 31 (7): 971–980, 2013.

[5] R. Volk, J. Stengel, F. Schultmann, Building Information Modeling (BIM) for existing buildings - literature review and future needs, *Autom. Constr.*, 43 (38):109–127, 2014.

[6] G. Lee, J. Won, S. Ham, Y. Shin, Metrics for Quantifying the Similarities and Differences between IFC Files, *J. Comput. Civ. Eng.*, 25 (2):172–181, 2011.

[7] Y. Pan, L. Zhang, A BIM-data mining integrated digital twin framework for advanced project management, *Autom. Constr.*, 124: 103564, 2021.

[8] Q. Lu, X. Xie, A.K. Parlikad, J.M. Schooling, Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance, *Autom. Constr.*, 118: 103277, 2020.

[9] H. Hamledari, B. McCabe, S. Davari, A. Shahi, Automated Schedule and Progress Updating of IFC-Based 4D BIMs, *J. Comput. Civ. Eng.*, 31(4):04017012, 2017.

[10] K. Mckinney, J. Kim, M. Fischer, C. Howard, Interactive 4D-CAD, In *Proc. Third Congr. Comput. Civ. Eng.*, pages 381–389, Anaheim USA, 1996.

[11] H.J. Wang, J.P. Zhang, K.W. Chau, M. Anson, 4D dynamic management for construction planning and resource utilization, *Autom. Constr.*, 13 (5):575–589, 2004.

[12] J.P. Zhang, M. Anson, Q. Wang, A New 4D Management Approach to Construction Planning and Site Space Utilization, In *Proc. Comput. Civ. Build. Eng.*, pages 15–22, California USA, 2012.

[13] B.G. de Soto, A. Rosarius, J. Rieger, Q. Chen, B.T. Adey, Using a Tabu-search Algorithm and 4D Models to Improve Construction Project Schedules, *Procedia Eng*., 196:698–705, 2017.

[14] C.Z. Li, F. Xue, X. Li, J. Hong, G.Q. Shen, An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction, *Autom. Constr.*, 89:146–161, 2018.

[15] Y. Deng, V.J.L. Gan, M. Das, J.C.P. Cheng, C. Anumba, Integrating 4D BIM and GIS for Construction Supply Chain Management, *J. Constr. Eng. Manag.*, 145 (4):04019016, 2019.

[16] R. Vieira, P. Carreira, P. Domingues, A.A. Costa, Supporting building automation systems in BIM/IFC: reviewing the existing information gap, *Eng. Constr. Archit. Manag.*,27(6):1357–1375, 2020.

[17] J. Seo, I. Kim, Industry Foundation Classes-Based Approach for Managing and Using the Design Model and Planning Information in the Architectural Design, J. *Asian Archit. Build. Eng.*, 8 (2):431–438, 2009.

[18] B. Akinci, F. Boukamp, Representation and Integration of As-Built Information to IFC Based Product and Process Models for Automated Assessment of As-Built Conditions, In *ISARC Proc.*, pages 543–548, Washington, USA, 2002.

[19] W. Solihin, C. Eastman, Y.C. Lee, Multiple representation approach to achieve high-performance spatial queries of 3D BIM data using a relational database, *Autom. Constr.*, 81:369–388, 2017.

[20] R. Marmo, F. Polverino, M. Nicolella, A. Tibaut, Building performance and maintenance information model based on IFC schema, *Autom. Constr.*, 118:103275, 2020.

[21] J. Beetz, L. van Berlo, R. de Laat, BIMserver.org – An Open Source IFC Model Server, In Proc. of the *CIP W78 Conf.*, pages 24-39, Cairo, Egypt, 2010.

[22] Y.H. Lin, Y.S. Liu, G. Gao, X.G. Han, C.Y. Lai, M. Gu, The IFC-based path planning for 3D indoor spaces, *Adv. Eng. Inform.*, 27(2):189–205, 2013.

[23] L. Ma, R. Sacks, A Cloud-Based BIM Platform for Information Collaboration, In *ISARC Proc.*, pages 581–589, Auburn, USA, 2016.

[24] Neo4j Inc., Graph Database Use Cases: Neo4j for Graph Data Science and AI. Online: https://neo4j.com/use-cases/graph-data-science-artificial-intelligence/ (Accessed: 15/09/2021).

[25] B. Zhang, B. Yang, C. Wang, Z. Wang, B. Liu, T. Fang, Computer Vision-Based Construction Process Sensing for Cyber–Physical Systems: A Review, *Sensors.*, 21(16):5468, 2021.

[26] B. Yang, B. Liu, J. Xiao, B. Zhang, Z. Wang, M. Dong, A novel construction scheduling framework for a mixed construction process of precast components and cast-in-place parts in prefabricated buildings, *J. Build. Eng.*, 43:103181, 2021.

[27] Z. Wang, Q. Zhang, B. Yang, T. Wu, K. Lei, B. Zhang, T. Fang, Vision-Based Framework for Automatic Progress Monitoring of Precast Walls by Using Surveillance Videos during the Construction Phase, *J. Comput. Civ. Eng.*, 35 (1):04020056, 2021.