Modeling Civil Engineered Systems

Individual Project 1

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Introduction

Along with the increasing complexity in construction projects, integration has became the major factor of project performance[1][2]. Residential buildings are among the most complex, because of the close connection with our daily lives. They not only to organize various subsystems, such as the HVAC, water supply, and electrical systems, but also demand a high standard of performance evaluation, including sensitive environmental control and compliance with material standards.

The study aims to utilize ontology as a prototype of BIM softwares to enhance integration performance of building project in different stages of life cycle. In later chapters, the study also provides engineering challenges and construction example to further indicates the contribution of implementation of ontology.

Methods

Parametrization of the system

Background research

This ontology is created to indicate key factors information of low-level residential building, which enable architects, project or construction managers to systematically mange and navigate within major components (structural elements or basic facilities, etc.) of a defined building, mainly focus on architectural design and construction management, reducing the human error and facilitating the efficiency of construction project. In the following context, I mainly refer to previous researches[3][4] of basic concepts of both BIM and building system to construct the ontology.

No.	Colour	Building Concept
#1		Building Spaces
#2		Building Equipment & Systems
#3		Building Points & Measurements
#4		Building Physics
#5		Building Occupants
#6		Building Environments
#7		Building Affordances
#8		Building Features of Interest

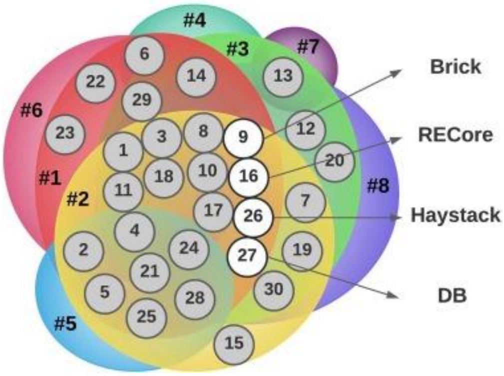


Figure 1

Building concepts and related domain ontologies[1]

The structure of the ontology could be divided into 2 major parts, including information of the building elements, which presents physical, functional, and logical decomposition of residential buildings, and another is relevant files or documents, including 3D models, floor plans, elevations and sections, etc.

To identify the decomposition of the system, we first need to define the main functions of residential buildings, which are providing safe accommodation and comfortable spaces. To achieve that, elements like structure, facilities, building material and space types are necessary components. In most cases, the structure system of residential buildings configuration is consist of 2 major parts, including substructure (including foundation and plinth beam) and superstructure (including column, beam, wall and slab), with properties and attributes, including size, cost or construct stage. On the other hand, facilities, which could be refer to the 2nd important concept in Figure 1[3] like HVAC system or water pipelines are also key factors to the indoor comfort and provide critical resources to users.

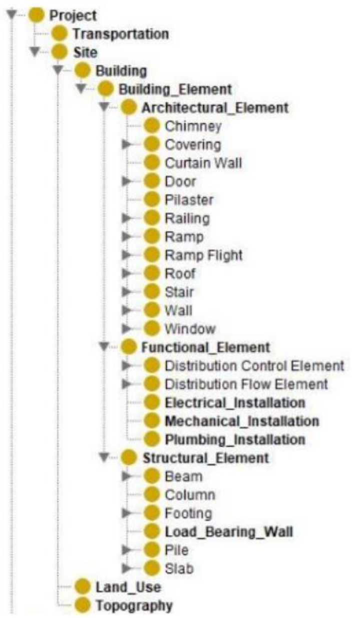


Figure 2

Basic concept/class hierarchites for BIM and GIS integraiotn[4]

For building material, I only focus on those are crucial to the structure system, and also properties like amount, cost, etc.

Except for those physical concepts, space type, which could be refer to the 1st important concept in Figure 1[3], is a rather abstract one, while it fill in the gap of relationship between physical elements and users behavior. In fact, the concept of building spaces is twofold[3]. To cover the general situation, I choose common-use components, including parking space for the outside environment, room types for inside space.

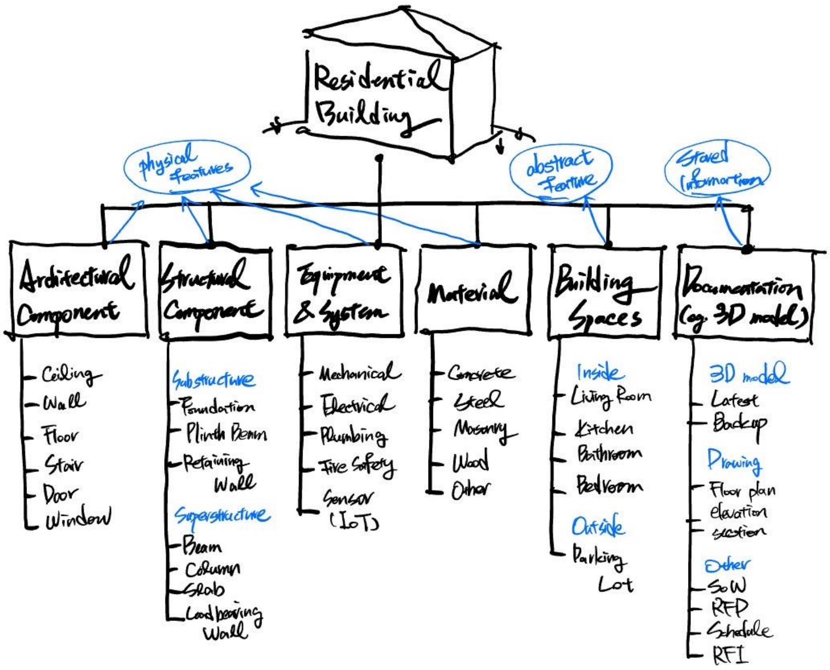
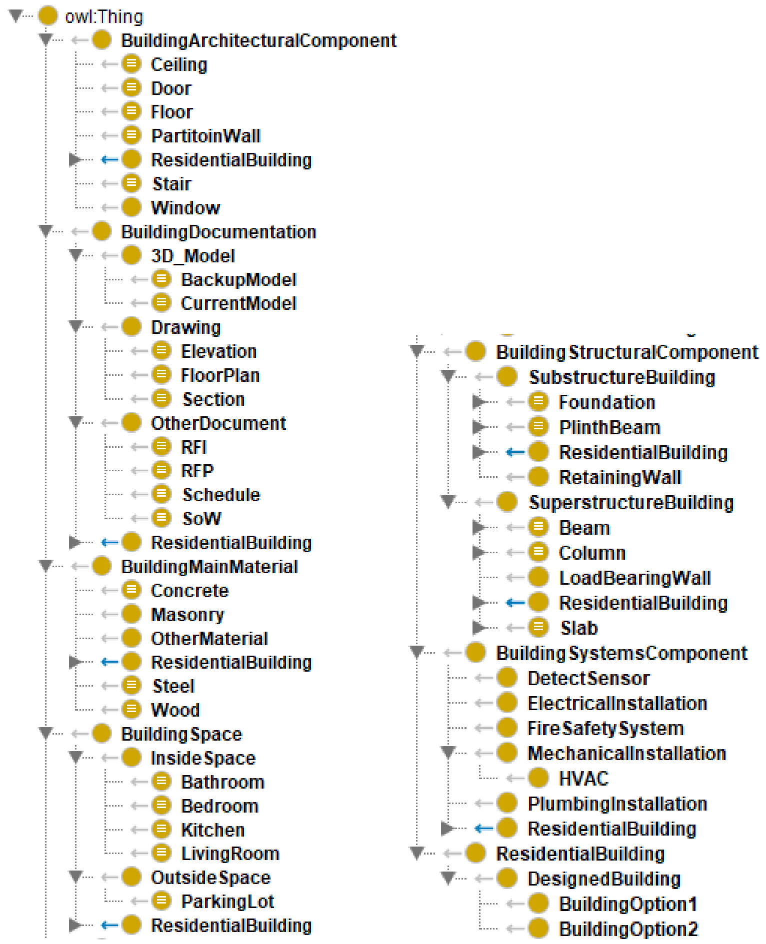


Figure 3 Simple sketch of the ontology structure

Axiom implementation of Protégé

Axiom	Protégé syntax
Individuals	Individuals
Atomic concept	

<table>
<tr><td>Individual name</td><td>BackupModel_BuildingOption1
BackupModel_BuildingOption2
BathroomOption1
BathroomOption2
Beam_C-shapedSteel
BeamOption1
BeamOption2
BedroomOption1
BedroomOption2
BuildingOption1
BuildingOption2
C-shapedSteel
CeilingOption1
CeilingOption2
CLTWood
Column_C-shapedSteel
ColumnOption1
ColumnOption2
ConcreteOption1
ConcreteOption2
CurrentModel_BuildingOption1
CurrentModel_BuildingOption2
Elevation_BuildingOption1
Elevation_BuildingOption2
FloorOption_General
FloorOption_Outdoor
FloorPlan_BuildingOption1
FloorPlan_BuildingOption2
Gate
InsideDoor
InteriorWood
IsolatedFooting
KitchenOption1
KitchenOption2
LivingRoomOption1
LivingRoomOption2
LoadBearingWall
LSFSlab
Masonry
ParkingLotOption1
ParkingLotOption2
PartitionWallOption1
PartitionWallOption2
PlinthBeamOption1
PlinthBeamOption2
RCBeam
RCColumn
RCSlab
RCStair
Rebar
RFI_BuildingOption1
RFI_BuildingOption2
RFP_BuildingOption1
RFP_BuildingOption2
RoundColumnOption1
RoundColumnOption2
Schedule_BuildingOption1
Schedule_BuildingOption2
Section_BuildingOption1
Section_BuildingOption2
SoW_BuildingOption1
SoW_BuildingOption2
SteelBeam
SteelColumn
SteelStair
StripFooting
Window</td></tr>
<tr><td>Roles</td><td>Object Properties</td></tr>
<tr><td>Atomic role</td><td>
hasArchitecturalComponent
hasDocument
hasDrawing
hasElevation
hasFloorPlan
hasSection
hasModel
hasBackupModel
hasCurrentModel
hasOtherDocument
hasRFP
hasSoW

hasMainMaterial
hasSpace
hasInsideSpace
hasOutsideSpace
hasStair
hasStructuralComponent
hasSubstructure
hasFoundation
hasPlinthBeam
hasSuperstructure
hasBeam
hasColumn
hasSlab

hasSystemComponent
</td></tr>
<tr><td>Inverse role</td><td>
isArchitecturalComponent
isDocumentOf
isDrawingOf
isElevationOf
isFloorPlanOf
isSectionOf
isModelOf
isBackupModelOf
isCurrentModelOf
isOtherDocumentOf
isRFPOf
isSoWOf

isMainMaterialOf
isSpaceOf
isInsideSpaceOf
isOutsideSpaceOf
isStairOf
isStructuralCompnentOf
isSubstructureOf
isSuperstructureOf
isSystemComponentOf
</td></tr>
</table>

Concepts	Classes
Top concept	Domains (intersection) OtherDocument Domains (intersection) Drawing Domains (intersection) 3D_Model Domains (intersection) ResidentialBuilding Domains (intersection) OutsideSpace Domains (intersection) InsideSpace Domains (intersection) SuperstructureBuilding Domains (intersection) SubstructureBuilding Domains (intersection) BuildingArchitecturalComponent Domains (intersection) BuildingSystemsComponent
Bottom concept	Ranges (intersection) ResidentialBuilding Ranges (intersection) OtherDocument Ranges (intersection) 3D_Model Ranges (intersection) Drawing Ranges (intersection) OutsideSpace Ranges (intersection) InsideSpace Ranges (intersection) BuildingArchitecturalComponent Ranges (intersection) BuildingSystemsComponent Ranges (intersection) BuildingMainMaterial
Existential restriction	Class：DesignedBuilding hasSubstructure some SubstructureBuilding hasArchitecturalComponent some BuildingArchitecturalComponent hasMainMaterial some BuildingMainMaterial hasDrawing some BuildingDocumentation hasSystemComponent some BuildingSystemsComponent hasSpace some BuildingSpace hasSuperstructure some SuperstructureBuilding Class：BuildingOption1、BuildingOption2 hasSubstructure some Foundation hasSubstructure some PlinthBeam hasSuperstructure some Beam hasSuperstructure some Column hasSuperstructure some Slab hasSystemComponent only BuildingSystemsComponent (hasOtherDocument some SoW) or (hasOtherDocument some RFP)
Universal restriction	Class：BuildingOption1、BuildingOption2 hasSystemComponent only BuildingSystemsComponent
at-most restriction	Class：BuildingOption1、BuildingOption2

	hasCurrentModel max 1 CurrentModel hasBackupModel max 10 BackupModel
Nominal	Class：BuildingOption1 hasBeam value RCBeam hasColumn value RCColumn hasCurrentModel value CurrentModel_BuildingOption1 hasElevation value Elevation_BuildingOption1 hasFloorPlan value FloorPlan_BuildingOption1 hasFoundation value StripFooting hasPlinthBeam value PlinthBeamOption1 hasSection value Section_BuildingOption1 hasSlab value RCSlab hasStair value RCStair Class：BuildingOption2 hasBeam value Beam_C-shapedSteel hasColumn value Column_C-shapedSteel hasCurrentModel value CurrentModel_BuildingOption2 hasElevation value Elevation_BuildingOption2 hasFloorPlan value FloorPlan_BuildingOption2 hasFoundation value IsolatedFooting hasSection value Section_BuildingOption2 hasSlab value LSFSlab hasStair value SteelStair

Table 1 Axioms and corresponding applications

Application of Noy & McGuiness's suggestions

1. **Decide the use and users of the ontology first**

   To start thinking about the structure of the ontology, I first define the use(being a prototype of BIM software), purpose(easy to manage residential building projects and facilitate the efficiency) and possible users(architects or managers) of it, which provide a solid foundation for the later convergence of the ontology.

2. **Reusing existing ontologies and use top- down development process**

   I refer to the previous researches[3][4], and use the top-down development process to identify classes and relations of them, making sure the class hierarchy is thoughtful and key concepts of BIM or residential buildings are well included..

3. **Concepts in the ontology are close to objects and also limit the scope**

   I try to limit levels of my class hierarchies within 4, and focus only on the key scopes, not only to make the structure easy to navigate and utilize, but also present strong logic and intention for other users to follow.

4. **Disjoint subclasses**

   Because BIM is aimed to integrate physical elements of buildings with relevant documentation and 3D model, resulting in a complicated system to manage.

Therefore, it's important to clearly specify the classes are disjoint, enabling the system to the validate the ontology.

Engineering challenge

Challenges arise at different stages of the lifecycle of residential buildings. For example, during the early Product Stage, the design and tendering processes require architects, contractors, and material suppliers to collaboratively coordinate and propose plans for the requirements of SoW and RFP. During the Construction Stage, issues related to the integration of interfaces between different subcontractors may emerge, particularly challenges arising from multiple trades working simultaneously in the same location. In the later Use Stage and End-of-Life Stage, the need for maintenance and operation requires collecting data from various building subsystems and components for integrated analysis.

Building life cycle																Supplementary information
Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction Demolition	Transport	Waste processing	Disposal	Re-use-Recovery-Recycling-potential

Table 2 Building life cycle stages[5]

In fact, analyzing the composition of certain object through ontology has become a common approach in many aspects of modern society[6], including engineering management. For example, concepts such as BIM, IoT, and Smart Buildings all leverage ontology to establish theoretical frameworks, which are then further applied to address the integration challenges mentioned above.

Environmental interfaces

Buildings often need to exchange information and integrate with other systems in various contexts, while the ontology in this study focuses on the system decomposition and relevant documentation, with practical applications including examples such as BIM modeling or Digital Twins. Following section will provide explanations from the perspective of the building lifecycle.

Construction stage：Interface with stakeholders

During the construction phase, stakeholders often use BIM for design integration while also frequently utilizing Project Management Information System(PMIS), like Procore. As noted, *"As construction projects become bigger, PMIS is being used as a project collaboration tool for project participants, owners, designers, inspectors, and contractors."* [8].

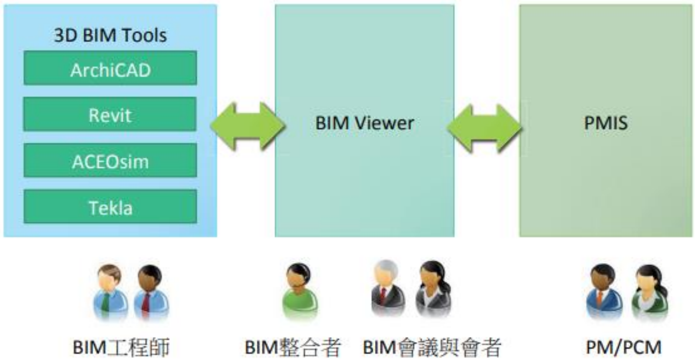


Figure 4 BIM+PMIS integration diagram[7], BIM engineer, BIM coordinator & BIM meeting participant, PM/PCM(left to right)

Compared to BIM or other 3D modeling softwares, which focus on the product itself (in this study, residential buildings), PMIS is an information system designed to meet project management needs. It centers on tasks derived from the full scope of the project and extends to other components, such as project scheduling, resource management, and deliverables.

While in theory, the integration of BIM and PMIS can enhance project efficiency, in practical applications, the lack of standardized information exchange interfaces among stakeholders can lead to challenges in the integration process, ultimately falling short of achieving the intended results.

Use stage：Interface with infrastructure system and BIM models

Once a building enters the Use Stage, the demand for energy, such as water, electricity, and heating, becomes urgent. Therefore, we not only need to integrate hardware interface with existing infrastructure system, to reach the net zero goal, we could also further expand the implementation of the ontology into a broader urban scale. Research[9] has shown that the building ontology could further incorporate the BIM models into FMI(Functional Mockup Interface)-based UBEM (Urban Building Energy Modeling), which helps the evaluation of demand response strategies and its potential to shed peak loads.

For example, this could involve integrating EnergyPlus with BIM models or other 3D modeling software at the urban scale, utilizing the tool to estimate and manage urban energy demand.

Results and Discussion

3 Engineering implementation example

The following explores the potential applications of the ontology through three engineering case studies analyzed from different perspectives. ：

Scenario： Construction management

Use Case： Ontology could be used for design integration between stakeholders. Figure 6 presents the process of integrating BIM and PMIS, presenting BIM as a database for PMIS. By recreating the basic structure of BIM, users could update documentations into the ontology, like 3D models, drawings or RFI, and further integrate with PMIS system. So that it not only be able to facilitate construction progress and prevent safety accidents, and reduce cost[8].

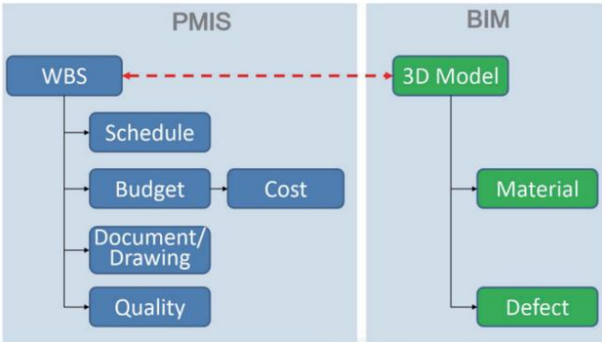


Figure 5 PMIS+BIM system integration[7]

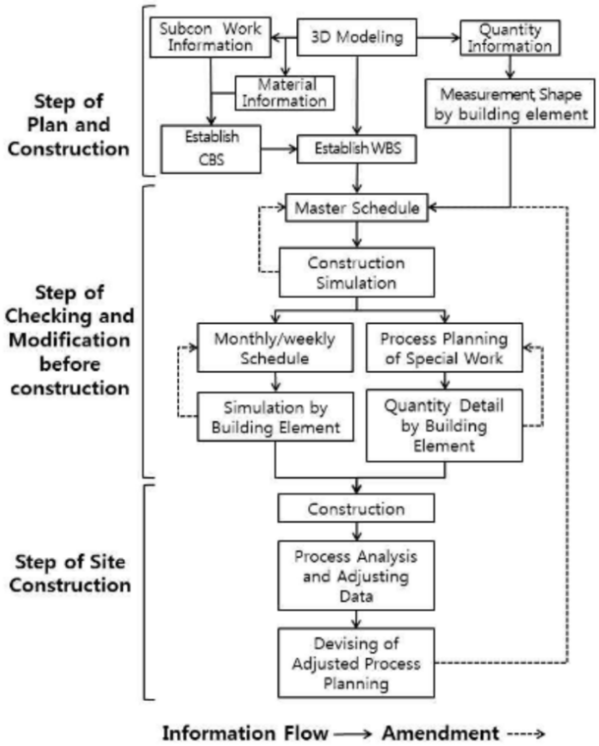


Figure 6 BIM based PMIS process[8]

Scenario： Building energy management

Use Case： To accurately control the energy consumption of building, we could install sensors in to different spaces, and integrate the data(detect value and room name where sensors located) into the class "Sensors" of the ontology. Furthermore we could implement high-intensity observation plans to monitor real-time energy consumption, which enables analysis of energy performance over time, providing valuable insights for optimizing energy systems in the future.

Scenario： Building renovation

Use Case： Residential buildings often face renovation needs in the later stages of their lifecycle, whether for interior design adjustments or demolition and reconstruction.*" Renovation tends to be associated mainly with the building envelope and the process of improving or modernizing a building to return it to a good state."*[10] Thus, understanding the building's state is a crucial prerequisite for any renovation project[11].

By utilizing information on structure properties, such as tagging the production and usage dates of steel structures, it becomes easier to predict material aging and expedite renovation projects. And we could establish a fully functional BIM model based on the ontology to share, clarify, and unify the perception of the renovation process by all stakeholders including building occupants, allowing better visualization, communication, and decision-making through 3D-based simulations of several renovation scenarios and strategies[12].

Conclusion

The research addresses key challenges of integration issues within AEC industry, including construction management, energy consumption optimization, and renovation planning, while demonstrates the potential of ontology-driven approaches by providing comprehensive solutions. Especially for large-scale construction projects, a well-structured ontology that connect 3D models and building information, could greatly improve collaboration among stakeholders, by the combination of BIM and PMIS.
Case studies also highlight the versatility of the ontology, from enabling better decision-making in construction progress to enhancing energy performance monitoring through real-time data integration.
Furthermore, aforementioned results also provides direction for future research：

1. Standardizing interfaces for data exchange between BIM, PMIS, and other systems to further enhance integration.
2. Expanding the application of the ontology to urban scale contexts, which could provide insights and utilities for sustainable city vision.

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