HETEROGENEOUS DATA PROCESSING TO SUPPORT BIM INTEROPERABILITY AND PROJECT MANAGEMENT IN THE ARCHITECTURE, ENGINEERING, AND CONSTRUCTION (AEC) DOMAIN

by

Ran Ren

A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

School of Construction Management Technology

West Lafayette, Indiana

December 2021

THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Jiansong Zhang, Chair

Department of Construction Management Technology

Dr. Hubo Cai

Lyles School of Civil Engineering

Dr. Yunfeng Chen

Department of Construction Management Technology

Dr. Hazar Nicholas Dib

Department of Construction Management Technology

Dr. Yi Jiang

Department of Construction Management Technology

Approved by:

Dr. Kathryne Newton

To my parents, who support my any decisions at anytime, taught me how to be a nice and polite person, and foster me with full of love.

To my grandparents, who gave me a blissful childhood, left me a lot of valuable memories in my mind. I miss you so much.

To my husband, who I met and fell in love with in Chicago, always supports me, and let me understand what the soul mate is.

To my two cats, eggplant and cake, who join our family and bring happiness to me.

To myself, who never give up and chase her dream.

ACKNOWLEDGMENTS

First and foremost, I would like to express my profound gratitude to my advisor Prof. Jiansong Zhang for his guidance, help, supports, and advice. It has been an honor to be his first female Ph.D. student at Purdue University. He provided me an opportunity to join construction management domain four years ago, and he has always believed in me and taken good care of me. Without his persistent help and guidance, my studies and dissertation would not have been completed.

I would like to pay my special regards to my committee members Prof. Hubo Cai, Prof. Yunfeng Chen, Prof. Hazar Nicholas Dib, and Prof. Yi Jiang for their insightful advice, precious time, and constructive comments.

I also would like to thank my husband and parents, for being supportive and patient during my Ph.D. study. Their encouragement, trust, and unconditional supports provide me power to improve myself and never give up.

I gratefully acknowledge the National Science Foundation (NSF) and the Purdue University that generously supported my research. This material is based on work supported by the NSF under Grant No. 1745374. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the NSF.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEFINITIONS

Architecture, engineering, and construction (AEC). “The sector of the construction industry that provides the services on the architectural design, engineering design and construction services. It is a sector which is very active in the adoption of Information, Communication and Technology. This is also a sector which is very active in the international arena.” (IGI Global 2021).

Building Information Modeling (BIM). “Shared digital representation of physical and functional characteristics of any built object which forms a reliable basis for decisions” (Braila et al. 2021).

Industry Foundation Classes (IFC). Industry Foundation Classes (IFC) is registered as ISO 16739. It is the most widely used and non-proprietary exchange format that represents building information (Volk et al. 2014).

Information Extraction (IE). Information extraction aims to discover structured information in textual contents, and develop a predefined relational schema that has predetermined underlying semantics to detect the values of records in a single or a collection of textual documents (Fagin et al. 2016).

ABSTRACT

A portion of this section was previously published by:

“A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions.” *Advances in Civil Engineering*, 2021.
https://doi.org/10.1155/2021/8824613

Recent years have witnessed the exponential growth of the Architecture, Engineering, and Construction (AEC) industry, especially in its capability to generate, collect and process data in the life cycle of a construction project. In the AEC domain, there are many tasks, including architectural design, structural analysis, and construction management, to name a few. Therefore, the identification of the knowledge gaps between AEC tasks or within one task is important to help develop solutions to support various AEC applications (e.g., construction monitoring). Advances in scientific data collection, the new generation of sensor systems, such as radio frequency tags and bar codes, have generated a flood of data to support information management in the construction domain. As the construction industry is adapting to new computer technologies in terms of hardware and software, heterogeneous data is becoming more and more available for access to bridge the gaps in the construction domain (e.g., Building Information Modelling (BIM) interoperability) and facilitate construction tasks (e.g., construction document information extraction). BIM is an integrated informational process and plays a key role in enabling efficient planning and control of a project in the AEC domain. Industry Foundation Classes (IFC) provides a useful data structure for BIM data communication and exchange. IFC-based BIM allows building information to be more interoperable among different BIM applications. BIM interoperability refers to the ability of two separate software programs or management systems to communicate and exchange information/data with each other. The advantage of BIM interoperability offers the seamless information/data transfer, and it could abstract necessary information/data, remove redundancy and duplicate information/data at the early design phase of the construction project. IFC-based BIM models are the models of buildings using the open IFC international standard which by itself is extensible. The BIM interoperability problem is both a technical problem and a management problem. From the technical dimension, it is focused on the software workflows which use different BIM applications. From the management dimension, it is reflected in the actual

use of information/data between architectural design and structural analysis processes in the AEC domain. To address that, the author focused on exploring information missing and/or information inconsistency between different BIM applications as the gap-driven analysis, and discussed it from both technical and management dimensions. In addition, to support information management and facilitate different tasks and applications in the construction domain, the author explored the deeper information needs of construction applications from construction monitoring perspective, provided the solutions [e.g., ontological model, and information extraction (IE) method] to better manage construction site information to support construction monitoring applications.

CHAPTER 1 - INTRODUCTION

A portion of this chapter was previously published by:

"Semantic Rule-Based Construction Procedural Information Extraction to Guide Jobsite Sensing and Monitoring." *Journal of Computing in Civil Engineering*, 35(6), 04021026. DOI: 10.1061/(ASCE)CP.1943-5487.0000971

"Comparison of BIM Interoperability Applications at Different Structural Analysis Stages." In *Construction Research Congress 2020: Computer Applications* (pp. 537-545). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784482865.057

1.1 Overview and Motivation

A major part of construction project data is stored in textual documents and virtual models, including contracts (Al Qady and Kandil 2010), specifications (Akanbi and Zhang 2021), 3-Dimensional models (Akanbi and Zhang 2022), 4-Dimensional models (Zhang and Laddipeerla 2018), building information models (BIMs) (Wong Chong and Zhang 2021), among others. Different types of construction documents/models provide different information and play different roles in a construction project. Leveraging heterogeneous data in the construction domain can support various applications, such as engineering and management analysis, automation in construction, and education innovation (Ren et al. 2021b; Ren et al. 2020). BIM facilitates a procedural change to share information/data in all the phases of the life cycle of a building in the Architecture, Engineering, and Construction (AEC) domain. BIM interoperability possesses a great advantage in designing, analyzing, and managing construction projects. Based on the definition by European Interoperability Framework (EIF) "Interoperability means the ability of information and communication technology (ICT) systems and of the business processes they support to exchange data and to enable the sharing of information and knowledge" (Framework 2004). Traditionally, information/data sharing in a construction project uses the method that directly exchanges proprietary file formats. For example, the file type could be from .doc to .pdf, or from .jpg to .pdf. But the appropriate information/data could not be transferred successfully in such a straightforward way which is just changing file formats from one type to another (Howell and Batcheler 2005). Among the techniques that are adopted in the construction domain, BIM provides a platform for representing different types of information to support various applications, such as Industry Foundation Classes (IFC) model for information checking and information extraction (Wu and Zhang 2019; Zhang and El-Gohary 2015). Information extraction (IE) automatically extracts structured information from unstructured or semi-structured documents to support various construction applications (e.g., code compliance checking). In the AEC domain, researchers put much efforts on IE from building codes and legal documentations (Lee et al. 2020; Zhang and El-Gohary 2013), whereas they seldom focused on construction procedural documents (e.g., specifications) that could have been used as an important data source in the construction process and applications. In order to better represent and exchange BIM-based information/data in the AEC domain, in this dissertation, the author developed technical solutions (e.g., model information representation and model information checking) to support IFC-based BIM interoperability. The reason is that IFC is the most widely used and a non-proprietary exchange format to represent building information (Volk et al. 2014). Meanwhile, to reduce manual efforts in collecting information, the author proposed a semantic rule-based information extraction method to automatically extract construction execution steps from construction procedural documents to support various construction applications and tasks, to address the interoperability of textual data in addition to BIM data.

1.2 State-of-the-Art and Knowledge Gaps of Information Management in BIM Interoperability and Construction Monitoring

The 3-Dimensional modeling technology has been applied in the construction management domain for many years to improve the visualization and documentation of a construction project (Ma and Liu 2018; Dib et al. 2011). BIM is considered to play a key role in the AEC domain, which supports the visualization, documentation, and representation of the geometric, material and functional information in the life cycle phases of a building. Information represented by BIM can be processed and analyzed to support interoperable BIM usage between different applications (e.g., architectural design and structural analysis). Figure 1 shows the system with and without applying IFC-based BIMs in the AEC domain. However, there are still some research gaps when implementing BIM into different applications. For example, information missing is still a research problem that needs to be solved in the different structural analysis steps, which is a critical problem in an interoperable use of BIM. It can affect (1) the efficiency and accuracy of information transfer, processing, and analysis, and (2) the structural analysis results.

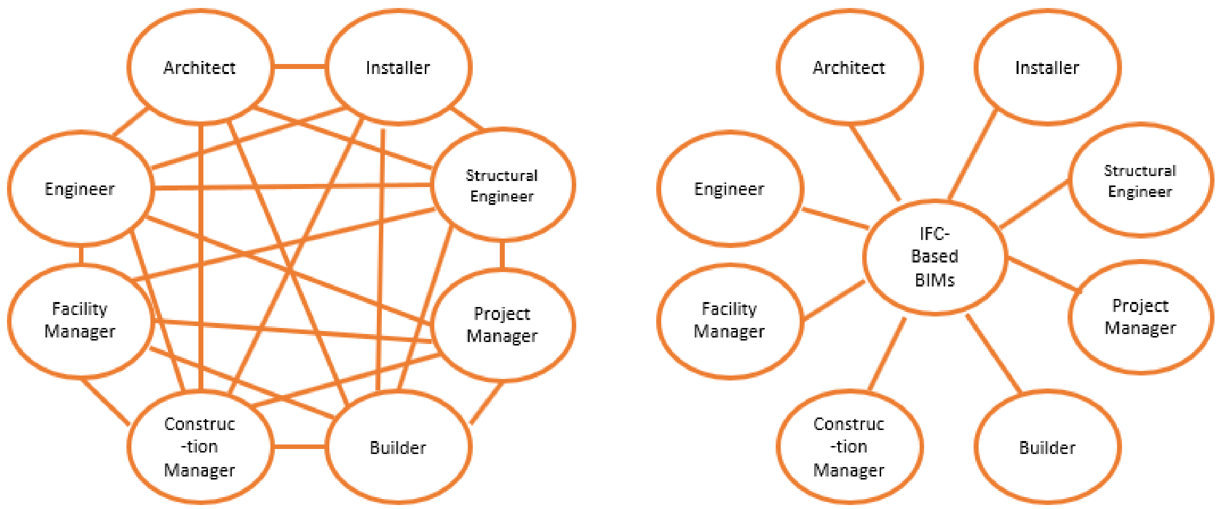


Figure 1. Interoperability system without (left) or with (right) IFC-based BIMs applications.

In addition, accurate and timely information backed by domain knowledge is essential to successful decision-making during process control and management at construction jobsites. Construction process monitoring plays an essential role in construction management both for the onsite and offsite scenarios. Usually, designated personnel need to compare the planned procedure in the instructional documents with the execution procedure on the jobsite for the existing construction monitoring systems. However, assessing the construction progress at a construction jobsite manually is time-consuming, labor intensive, and error-prone. Therefore, it is important to reduce manual efforts in collecting information from construction procedural documents, selecting appropriate sensing techniques to collect data on the jobsite, and giving in-time feedback for progress monitoring and compliance checking, to support construction application and information management.

1.3 Proposed Approach

In this dissertation, a new set of methods, systems, frameworks, and applications, including information analyses of BIM interoperability from technical and process dimensions, invariant signature-based information representation methods, Business Process Modeling Notation (BPMN)-based architectural-structural exploration, technical routes-based BIM information interoperability analysis, Model View Definition (MVD)-based information checking algorithm, stage-information-file (SIF) system to analyze three stages of structural analysis, construction procedural information extraction method, BIM-based construction application, and construction monitoring application are developed to support BIM interoperability and facilitate information management in construction monitoring applications.

1.4 Problem Statement

This dissertation aims to address the gaps in: (1) BIM interoperability from the technical dimension in the context of the process dimension, by exploring information acquisition in the context of developing the material signature to support model information conversion to improve interoperable BIM applications, delivering an architectural-structural analysis environment to test the developed invariant signature at the software level, developing a programing environment and a model information checking system to automatically extract, check, and report material information in an IFC model, developing a stage-information-file (SIF) system among three stages of a structural analysis procedure and testing the implications of the IFC models with real 3D structures to integrate different file types, information, and analysis stages, and developing an information checking, provision, and application process (ICPAP) framework to demonstrate an all-in-one-place information management framework; and (2) information management (i.e., ontological model, and information extraction method) to process construction procedural documents for supporting various AEC applications by proposing a semantic rule-based information extraction (IE) method to automatically extract construction execution steps from construction procedural documents, developing a construction procedure and data collection (CPDC) ontology to classify construction site information and provide the guidance on selecting sensing techniques for collecting jobsite data based on the extracted information, and proposing a construction procedural data integration (CPDI) framework, which could integrate textual data and sensed data to automatically conduct construction execution steps compliance checking.

1.5 Significance of the Research

As shown in Figure 1, before IFC-based BIMs are applied to the AEC domain, different users such as architects and engineers, relied on one-to-one communication, i.e., it limits the communicate among stakeholders, in which only two stakeholders are involved in each line of communication (Ren et al. 2018). After IFC-based BIMs are applied to the AEC domain, different users could leverage the one-to-many communication, which accelerated information/data representation and transfer between different stakeholders in a construction project.

In order to address this BIM interoperability issue, the author focused on analyzing information missing from the management dimension and information inconsistency from the technical dimension. Because in the real world, information missing will cause erroneous analysis results, such as in the data exchange between architectural design and structural analysis processes. And it may cause misunderstanding or inefficient communication between different stakeholders in a construction project. Information inconsistency often happened in the importation or exportation between different BIM authoring tools and analysis software. It will cause erroneous information transfer and misunderstanding between different stakeholders. Therefore, in order to support BIM interoperability applications, any information missing or altered information during the information transfer should be fixed for further use in the AEC domain. To address that, the author: (1) explored information acquisition in the context of developing the material signature to support model information conversion to improve interoperable BIM applications; (2) delivered an architectural-structural analysis environment to test the developed invariant signature at the software level; (3) developed a programing environment and a model information checking system to automatically extract, check, and report material information in an IFC model; (4) developed a SIF system among three stages of structural analysis procedure and tested the implications of the IFC models with real 3D structures to integrate different file types, information, and analysis stages. In addition, from the management dimension, the proposed technical routes with different combinations, and their applications to different project delivery methods provide new instruments for stakeholders in the industry to support their decision making.

In addition, at the information level, the intelligent data processing methods (e.g., information extraction and data analytics) enable the various construction applications (e.g., construction monitoring) to transform from a human intensive process to an automated one. Existing construction monitoring systems rely on designated personnel to compare the planned procedure in the instructional documents with the execution procedure on the jobsite. It requires major human efforts and is time-consuming, costly, and human error-prone. To reduce manual efforts in collecting information from construction procedural documents, selecting appropriate sensing techniques to collect data on the jobsite, and giving in-time feedback for progress monitoring and compliance checking, the author: (1) proposed a semantic rule-based information extraction (IE) method to automatically extract construction execution steps from construction procedural documents; (2) developed a construction procedure and data collection (CPDC) ontology to classify construction site information and provide the guidance on selecting sensing techniques for collecting jobsite data based on the extracted information; and (3) proposed a construction procedural data integration (CPDI) framework, which could integrate textual data and sensing data to automatically conduct construction execution steps compliance checking.

1.6 Assumptions

The proposed method is based on the following assumptions:

1. The targeted models (i.e., architectural models and structural models) would be in 3D BIM format.
2. The 3D BIM format models could be converted to an IFC format file which is the input file of the proposed method.
3. The interoperable system could be working with IFC files directly.
4. The proposed information management method (i.e., ontological model, and IE method) could be working with procedural documents of building constructions.

1.7 Delimitations

The scope of this research focuses on data interoperability and information management to better support construction management tasks and applications: (1) BIM interoperability, especially between architectural design and structural analysis processes in a construction project; and (2) information management, especially information extraction from construction procedural documents to support construction applications (i.e., construction monitoring and sensing technique selection). Therefore, the description of the interoperable systems and algorithms in the method will focus on IFC-based BIMs only. In addition, the information extraction algorithm in the method will focus on construction procedural documents (i.e., specifications) only. Two special phases (architectural design and structural analysis) were selected because: (1) architectural design happens at an early stage of a construction project, and architects are the important stakeholders to plan, design and oversee the construction of buildings; and (2) structural analysis could simulate the performance of a building under different types of loads to make sure the structure of the building is safe. Structural engineers are in charge of creating structural models and making sure the architectural models could be achievable. The Construction Specifications Institute (CSI) specification was selected to help develop and test the IE algorithm, because CSI is a national association of more than 8,000 construction industry professionals. Based on the presentation of Bristol Brewing Company at Lvywild School (2014), “CSI is a national association of more than 13,000 volunteers, including specifiers, architects, engineers, contractors, facility managers, product representatives, manufacturers, owners and others who are experts in building construction and the materials used therein. CSI was founded in March 1948 by the specification writers of government agencies who came together to improve the quality of construction specifications. The institute’s efforts were essential in improving construction specification quality so that it could meet the demands of the post-war construction boom.” In addition, CSI (2017) demonstrated that “CSI produces Standards and Formats that help users write quality specifications. There are many different construction product listing resources on the market, most use CSI MasterFormat to organize product listings, which helps designers find solutions that apply to the technical solution they are trying to achieve.” Specifications include detailed descriptions of construction work processes dedicated to a specific construction project. Based on the definition in the Dictionary of Architecture and Construction, a specification is, “a written document describing in detail the scope of work, materials to be used, methods of installation, and quality of workmanship for a parcel of work to be placed under contract; usually utilized in conjunction with working (contract) drawings in building construction” (Harris 2006). Execution steps from the construction specification play an important role in communicating construction procedure of specific tasks of a project to the job site personnel.

1.8 Article-Based Dissertation Statement

As an article-based dissertation, the author used three journal publications (Ren and Zhang 2021a; Ren and Zhang 2021b; Ren et al. 2021a), and five conference publications (Ren et al. 2022; Ren and Zhang 2021; Ren and Zhang 2020; Ren and Zhang 2019; Ren et al. 2018)

The author started the research on exploring knowledge gaps in BIM interoperability at the information analysis level (Ren and Zhang 2021a; Ren and Zhang 2020; Ren et al. 2018). Then the author developed technical solutions to facilitate data processing at the process level (Ren and Zhang 2021a; Ren and Zhang 2021b; Ren and Zhang 2019). Furthermore, the developed technical solutions are used and integrated to develop frameworks and/or systems to facilitate construction tasks and/or applications (Ren et al. 2022; Ren and Zhang 2021).

The 2018, 2020, and 2022 *Construction Research Congress* provided permission for me to publish these articles titled: "BIM interoperability for structural analysis" "Comparison of BIM interoperability applications at different structural analysis stages" and "A BIM information processing framework to facilitate enriched BIM applications" in this dissertation.

The 2019 and 2021 *ASCE International Conference on Computing in Civil Engineering (i3ce)* provided permission for me to publish these articles titled: "Model information checking to support interoperable BIM usage in structural analysis" and "An integrated framework to support construction monitoring automation using natural language processing and sensing technologies" in this dissertation.

The *Journal of Computing in Civil Engineering* provided permission for me to publish this article titled: "Semantic rule-based construction procedural information extraction to guide jobsite sensing and monitoring" in this dissertation.

The *Advances in Civil Engineering* provided permission for me to publish this article titled: "A new framework to address BIM interoperability in the AEC domain from technical and process dimensions" in this dissertation.

1.9 Summary

In summary, to bridge the technical and practical gaps in the heterogeneous data processing to support data interoperability and management in the AEC domain, the author leveraged different methodologies, tools, and techniques to explore the information needs, proposed and developed the solutions to facilitate information processing from the information analysis, data processing, and service/application perspectives, including BIM interoperability, and construction monitoring applications. In the BIM interoperability research, the author worked on identifying a large knowledge gap in terms of improving data interoperability measures, developing roadmaps to assess BIM applications from technical and management dimensions. To bridge the gaps of leveraging various information and resources on the construction sites, the author developed a semantic rule-based construction procedural information extraction method for a unified and fully automated analysis environment to support construction monitoring, in which both the textual and sensing data are integrated and analyzed. Figure 2 demonstrates the research development procedure with related articles and proposed approaches in each chapter in the dissertation where the author organized the contents at three levels: information level, process level, and service and application level. At the information level in Chapter 3, the author analyzed information need, identified knowledge gaps, and developed solutions to better support data interoperability in the AEC domain. At the process level in Chapter 4, the author aimed to bridge the research gaps and developed solutions to facilitate BIM interoperability and construction procedural information analysis. At the service and application level in Chapter 5, the author leveraged and integrated the proposed technical solutions to help develop all-in-one frameworks and interfaces to support BIM-based applications and construction monitoring applications.

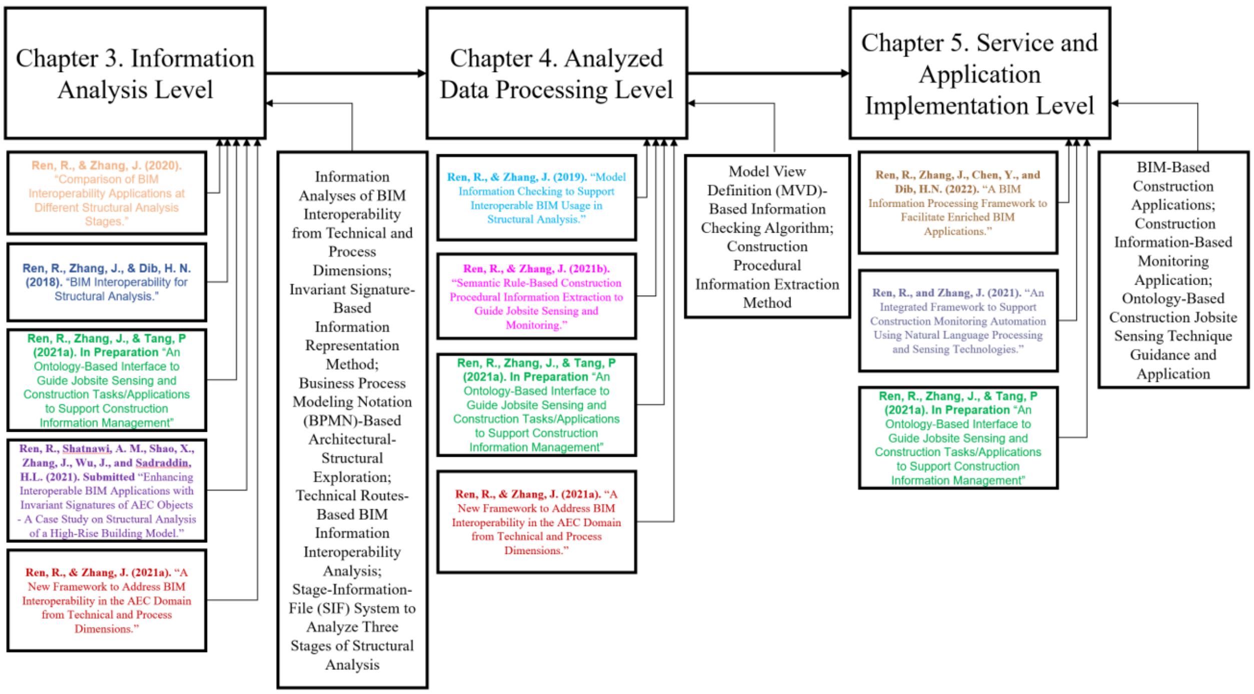


Figure 2. Dissertation chapters workflow with corresponding publications and proposed approaches in a visual way.

CHAPTER 2 - LITERATURE REVIEW

A portion of this chapter was previously published by:

"A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions." *Advances in Civil Engineering*, *2021*. https://doi.org/10.1155/2021/8824613

"Semantic Rule-Based Construction Procedural Information Extraction to Guide Jobsite Sensing and Monitoring." *Journal of Computing in Civil Engineering*, *35*(6), 04021026. DOI: 10.1061/(ASCE)CP.1943-5487.0000971.

"Comparison of BIM Interoperability Applications at Different Structural Analysis Stages." In *Construction Research Congress 2020: Computer Applications* (pp. 537-545). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784482865.057

"Invariant Signatures of Architecture, Engineering, and Construction Objects to Support BIM Interoperability between Architectural Design and Structural Analysis." *Journal of Construction Engineering and Management*, 147(1), 04020148. DOI: 10.1061/(ASCE)CO.1943-7862.0001943

2.1 BIM Interoperability Analyses and Applications

2.1.1 BIM and IFC Model View Definitions Application

BIM has been theorized by Prof. Chuck Eastman 45 years ago (Daniotti et al. 2020). In the AEC domain, a widely accepted and mature technical platform, which is based on an open standard, can enable communication and collaboration among different stakeholders without requiring them to have specific skills or proprietary applications. BIM provides the platform to transform the communication of participants in the AEC area from one-to-one paradigm to many-to-one paradigm. While BIM interoperability of a system with itself and/or with other systems is a constantly challenging issue in the AEC domain, it needs to be investigated both in the technical dimension and the process dimension (Ren et al. 2018).

IFC has been developed by an industry consortium since 1994. Since then, industry context, standardization organization, resource availability, and technology development of BIM application have exposed the standardization process to a dynamic environment centered around IFC (Laakso and Kiviniemi 2012). IFC model view definitions are specification documents that define exchange protocols between different BIM applications, by specifying a set of concepts and relationships needed for the exchange. Therefore, MVD can help BIM developers incorporate IFC compatibility into their software development (Akanbi et al. 2020). An MVD has two main parts: definitions and configurations. Definitions refer to the range of the possible concepts and relationships; whereas configurations refer to how the definitions should be used in a specific application context. For example, in the quantity take-off application context, the model of a concrete wall requires the following three possible relationships to be defined between 3D objects: disjoint, nested, or overlapping (Hietanen 2006). MVD is a useful construct for information checking of IFC data. Entity instances (e.g., "IfcMaterial") could be checked, and validation report will be created that lists entity instances and their numbers of occurrences (Ren and Zhang 2019). MVD tools provide a platform to implement MVD definitions and concepts. However, attributes of entity instances usually could not be directly checked using the MVD tool (e.g., IfcDoc software).

2.1.2 BIM Interoperability from Technical and Process Dimension Analyses

From the technical dimension, BIM interoperability indicates the ability of a technology to exchange data with other systems without major modification (Shirowzhan et al. 2020). BIM enables visualization techniques, such as augmented reality, to be applied to the AEC domain, for goals such as defect management, facility management, and preview of a built environment before construction (Chi et al. 2013; Park et al. 2013; Bae et al. 2013; Wang et al. 2013). BIM can be applied to energy modelling and energy simulation as well, where it has been identified there is a gap in conversion between BIM applications and energy modelling tools in construction management (Li and Zhang 2021; Kamel and Memari 2019; Gourlis and Kovacic 2017). The integration of Geographical Information System (GIS) with other techniques (e.g., real-time location system) for BIM application can improve the interoperability of different data types, for example, IFC model can be imported into GIS to be further processed (Guo et al. 2021; Lee et al. 2018; Isikdag et al 2008). In spite of the fast development of BIM, the AEC domain is still facing the problem of information missing between different BIM models, applications, and systems.

From the process dimension, BIM supports project management in procurement, construction, pre-fabrication and facility management, among others (Wong Chong and Zhang 2021; Wong Chong and Zhang 2019; Bryde et al 2013). Although BIM-based construction networks improve the communication among geographically separated participants, how to maintain collaboration that come from multiple disciplines and organizations is still a problem to solve (Liu et al 2017; Oraee et al 2017; Volk et al 2014). With the development of a growing number of universities beginning to offer BIM related courses in their AEC related programs, BIM becomes a promising vehicle for the education sector to introduce new information technology (Abbas et al. 2016; Clevenger et al 2010). To catalyst the development and harnessing of benefits mentioned above, information inconsistency between different stakeholders needs to be addressed to meet the BIM interoperability goal.

2.1.3 BIM for Architectural Design and Structural Analysis within the Context of Project Delivery Method

The integration of data, processes, and functions in a construction project is a major challenge that makes a technical development restrained by its process context (Ciribini et al. 2016; Chi et al. 2015). In construction there are many different types of project delivery methods which set the tone of a process context such as Design-Bid-Build (DBB), Design-Build (DB), Construction Management at Risk (CMR), Construction Management Agency (CMA), Construction Management Multi-Prime (CMMP), and Integrated Project Delivery (IPD). At the high level these methods can be organized into two categories based on whether the design and construction contracts are combined or separated, which dictate if the interaction between architectural design and structural analysis can be direct: (1) in DB and IPD, the design and construction contracts are combined, which allow architectural design and structural analysis to have direct and frequent interactions; whereas (2) in DBB, CMR, CMA, and CMMP, the design and construction contracts are separated, which render the interactions between architectural design and structural analysis indirect and less frequent. In practice, the selection of the best project delivery method depends on many factors such as the type of the project (e.g., residential, commercial, industrial, healthcare), the experience and preference of the owner and other stakeholders on different types of design and construction contracts (e.g., combined or separate), the weights of construction cost, schedule, quality, and financial risk in their consideration, the available physical and intellectual resources, etc. (Larsen et al. 2016; Lines et al. 2015). In the existing project delivery practice, an architectural model could not be directly used as a structural model. Structural engineers need to abstract useful information from the architectural model (or from the architects) to support the development of a structural model (Ülkeryıldız 2015). In addition, among all project delivery methods, the collaboration between architects and structural engineers is important, and their interactions are most likely to be frequent and iterative (Mujumdar and Maheswari 2018; Beazley et al 2017).

2.1.4 Knowledge Gaps for Architectural Design and Structural Analysis of BIM Interoperability

The AEC domain is meeting technical challenges in software interoperability and the amount of information or data types that need to be processed and communicated. Among the many phases and tasks in the AEC domain, architectural design and structural analysis are two important ones with the software and information interoperability between them being extensively researched. IFC is an open standard for information exchange between different BIM applications in the AEC domain. It represents project information in an interoperable way that contains geometric information, material information, and other physical and functional information needed of analyzing and managing a project. Structural analysis aims to simulate the structural performance of a building under different types of loads to make sure the structure is safe. Structural analysis relies on simplifications of a structure into simplified elements in a model, such as simplifying beams and columns as straight lines, and simplifying slabs as 2D shapes. The structural analysis model is a key element at the structural design stage of a construction project. It is used to simulate the performance of a structure under different types of external load scenarios to test the structural safety of the building. The steps of conducting structural analysis on the developed structural models integrate the intrinsic information (i.e., geometric information and material information), extrinsic information (i.e., supports information and external load information), and analysis information (i.e., structural analysis results). The needed information for structural analysis mainly includes geometric, material, and load information. Such information comes from architectural design and selected analysis scenarios. The information should be represented in an interoperable way to allow information transfer between different phases and different stakeholders. Table 1 shows a summary of example work on BIM interoperability between architectural and structural models.

Table 1. Example Work on BIM Interoperability between Architectural and Structural Models.

Issue	Literature
Information missing and information inconsistency	Sacks et al. (2010), Bank et al. (2010), Ramaji and Memari (2018), Ren et al. (2018)
Information missing and information inconsistency; Software function limitations	Hu et al. (2016), Aldegeily et al. (2018)
Software function limitations	Watson (2011), Yalcinkaya et al. (2014), Fleming (2016)
Model visualization limitations	Sanguinetti et al. (2012), Steel et al. (2012)
Geometric/spatial complications	Muller et al. (2017),
Other	Yang and Zhang (2006), Grilo and Jardim-Goncalves (2010), Nawari (2011), Solnosky et al. (2014), Shin (2017)

As shown in Table 1, there are several types of challenges in BIM interoperability between architectural design and structural analysis in the AEC domain. For example, information missing and information inconsistency (Sacks et al. 2010; Bank et al. 2010); software function limitations in information conversion (such as geometric information) (Fleming 2016; Yalcinkaya et al. 2014; Watson 2011); model visualization limitations in BIM interoperability (Sanguinetti et al. 2012; Steel et al. 2012); and the geometric/spatial complications (e.g., overlapping of structural parts in a model) that affect an efficient BIM interoperability (Muller et al. 2017).

The information-related challenges have been the focus of the research community. Various studies showed that between architectural design and structural analysis, there can be information missing and information inconsistency problems during the conversion of models between different software. For example, only geometric components of a model could be transmitted between Tekla structure (Trimble Company 2019) and Revit Architecture 2008, and cross-sectional properties were missing and must be set separately if there are many elements in a model (Sacks et. al 2010). Some preliminary tests showed that in SAP2000 (Computers and Structures 2019), the imported material information through an IFC file could not be loaded into a structural model to conduct structural analysis (Ren and Zhang 2019). Different types of boundary conditions in Revit (pinned, roller, and fixed) are treated as pinned when transferred to ETABS and SAFE

(Computers and Structures 2019; SAFE Software 2019; Aldegeily et al. 2018). BIM interoperability workflows/pathways between architectural design and structural analysis have been investigated by few researchers. For example, Ramaji and Memari (2018) summarized three workflows between BIMs and structural analysis models: (1) structural analysis models could be exported from BIM authoring tools directly; (2) BIMs could be imported into structural analysis tools to establish structural analysis model in reference to the architectural model; and (3) BIMs could be transferred to structural analysis models by a third-party application. Aldegeily et al. (2018) summarized three types of paths for data transfer between architectural and structural models: (1) "direct link using native file, which is the direct link between software programs from the same provider;" (2) "direct link using API, which is the data transfer with a BIM platform through its APIs;" and (3) "indirect link, which is the indirect transfer of information through third-party software or methods/algorithms." However, there is a lack of foundational methods that enable a seamless BIM interoperability between architectural design and structural analysis.

2.2 Construction Site Information Processing for Monitoring Applications

2.2.1 Textual Information Extraction

A large portion of construction project data is stored in textual documents, including contracts, specifications, meeting minutes, change orders, field reports, and requests for information, among others (Al Qady and Kandil 2010; Caldas et al. 2002). Different types of construction documents provide different information and play different roles in a construction project. For example, manufacturer instructions provide technical information of an equipment, which can be used as a guidance for equipment operation to diminish human risks; contractor method statements describe a means of controlling specific health and safety risks that have been identified, which is widely used for risk control and assessment; designer specifications demonstrate a list of bullet points depicting a process for developers to implement; and customized standard operating procedures define how the employees are expected to operate to achieve the desired outcome for maintaining consistent quality or a standard experience of a project (Clough et al. 2015).

Information Extraction work largely began with the DARPA Message Understanding Conference in 1978 (Grishman and Sundheim 1996), which aims to discover structured information in textual contents, and develop a predefined relational schema that has predetermined underlying semantics to detect the values of records in a single or a collection of textual documents (Fagin et al. 2016). The state-of-the-art semantic IE studies include four major tasks based on the level of complexity: (1) named entity extraction; (2) attribute extraction; (3) relation extraction; and (4) event extraction (Zhang and El-Gohary 2016). IE acts as a key technology in various natural language processing (NLP) applications, such as machine translation, question-answering, text summarization, and opinion mining (Singh 2018). IE can be used for: (1) healthcare industry to automatically extract information from doctors' prescriptions to support clinical decisions (Wang et al. 2018); (2) business analyses to help a set of analysis tools and support better decision makings by extracting various data from clients (Esser et al. 2014); and (3) the education domain to automatically extract information from students' submissions to help with grading (Sukkarieh and Pulman 2005), among others. In the AEC domain, researchers put much efforts on IE from building codes and legal documentations, whereas they seldom focused on construction procedural documents (e.g., specifications) that could have been used as an important data source in the construction process. In addition, monitoring the construction execution process based on specified procedures in regulatory documents is important for ensuring construction quality, and it requires extensive domain knowledge (Zhong et al. 2020).

There are two approaches to implement IE, which utilize rule-based and machine learning-based methods, respectively (Moens 2006). A rule-based method requires manual efforts to analyze the text features, such as syntactic features (e.g., part-of-speech tag) and semantic features (e.g., concept from an ontology) (Xue et al. 2022; Xue and Zhang 2020), and compile extraction patterns consisted of these features (Zhang and El-Gohary 2012). Customized IE rules are then applied to the textual data based on the predefined patterns to identify and extract necessary information. A supervised machine learning-based method requires manual efforts to collect a large set of training data with annotations of expected extraction results (Xue and Zhang 2021). Machine learning algorithms are then applied to automatically learn patterns and models for extracting information. Although a machine learning-based method can save manual efforts in pattern definition and extraction rule development, it requires a large set of annotated training data that are not easily available or accessible and, in most cases, proprietary (Zhou and EI-Gohary 2017).

2.2.2 Sensing Technique

Traditional scheduling and progress monitoring techniques (such as bar charts and the critical path method) could not provide information that pertains to the spatial aspects of a construction project (Poku and Arditi 2006). Therefore, geographical information systems (GIS), which is a database system with specific capabilities for spatially referenced data, and Global Positioning System (GPS), which provides geolocation and time information to a receiver anywhere on the earth, can be used for supporting construction progress visualization in three dimensions (Poku and Arditi 2006). In addition, due to the desired properties such as safety, high accuracy, and easiness to deploy, numerous distance sensing systems, such as acoustical distance sensors, thermal range detectors, laser detection and ranging (LADAR), light detection and ranging (LIDAR), laser scanners, photogrammetry, and 3D range imaging cameras, have become the predominant methods to collect range information in the construction and transportation sectors (Baker et al. 2019; Ajayi et al. 2018; Teizer 2008). Meanwhile, wearable sensors, such as inertial measurement unit (IMU), electromyography (EMG), accelerometer and gyroscope sensors, are very sensitive to the movement of the device and have been used in recent years for construction activity recognition due to its versatility and portability (Bangaru et al. 2020; Yan et al. 2017; Akhavian and Behzadan 2016). Similarly, radio-frequency identification (RFID) and radio-frequency (RF) tags provide an active and accurate way to track and locate materials and components in the construction field to better manage information on the jobsite (Ren et al. 2011; Ergen and Akinci 2007). Other techniques, for example, augmented reality (AR) and virtual reality (VR) have shown a great usage in the construction domain to solve a variety of management issues, such as in construction project scheduling, progress tracking, worker training and management, and visualization for construction applications (Ahmed 2019). In addition, computer vision-based progress detection using images and videos has made much advancement during the past decade. The state-of-the-art applications in computer vision focused on four main areas: (1) object detection, (2) image classification, (3) object segmentation, and (4) pose estimation (Wiley and Lucas 2018). However, limitations persist in computer vision due to limited availability of annotated datasets and objects that can be detected (Yu et al. 2020; Coluccia et al. 2019). Similarly, each sensing technique has different performance and requirements in terms of application, cost, precision, bandwidth, and measurement range (Ziegler et al. 2009). Therefore, different types of information on the jobsite require different techniques for collection. For example, distance information can be obtained using photogrammetry, and object detection can be conducted with computer vision (Fang et al. 2020; Piñeres-Espitia et al. 2017). It is essential to leverage suitable sensing techniques for acquiring corresponding field data to support the monitoring and control of construction jobsites.

2.2.3 Construction Monitoring

Progress monitoring has been repeatedly recognized as one of the essential factors in the success of construction projects (Deng et al. 2020; Pazhoohesh and Zhang 2015). Progress monitoring mainly relies on manually collecting daily, weekly, and monthly reports that are written by field personnel (Roh and Peña-Mora 2011). Traditional methods to monitor construction operations rely on observations (e.g., interviews, supervision and surveys) to analyze productivity and performance on the jobsite (Sherafat et al. 2020; Kim et al. 2019). It is time consuming and human error prone. Automation plays a key role among factors that made the manufacturing industry more productive, and it became a popular topic in construction monitoring in recent years (Asadi and Han 2018). Most of the researchers focused on improving automated construction monitoring by introducing new tools and techniques into construction site at the visual/graphic information level, such as integrating BIM, Unmanned Aerial Vehicles (UAVs) and sensors to obtain real-time data to construct 3D and 4D models for monitoring (Ibrahim and Golparvar-Fard 2019; Asadi and Han 2018; Anwar et al. 2018; Akanmu and Zhang 2016), and integrating interferometric synthetic aperture radar (InSAR) method (or SAR sensors) for mapping ground to capture fine spatiotemporal resolution images covering vast areas for monitoring (Serrano-Juan 2017; Yang et al. 2017). There is a lack of research on automated construction monitoring based on textual information from construction procedural documents. Moreover, applicability in real-time data acquisition of construction projects remains a challenge in the construction management domain (Omar and Nehdi 2016).

2.2.4 Information Management

Because of the dynamic nature of construction projects, the ability to exchange and integrate different types of information from different sources is important to facilitate their use in different construction processes (e.g., design and facility management) (Caldas and Soibelman 2003). The main challenge in construction information management is the presence of a variety of data types, including structured data files, semi-structured data files, unstructured text data files, unstructured graphic files, and unstructured multimedia files, to name a few (Wang et al. 2022; Su 2007). Therefore, it is an imperative issue to support different information types for various applications on the construction jobsites (e.g., process control and manufacturing, detecting and preventing risks), which can be improved by adopting sensor networks and sensor information management methods to help collect and process data (Thuraisingham 2004). Many researchers put efforts into text visualization and processing for construction information management (Xue et al. 2022; Nojedehi et al. 2021; Sun et al. 2020); some focused on Building Information Modeling (BIM)-based information management systems to support various applications, such as demolition and construction project and asset management (Xu et al. 2019; Chen and Lu 2019; Li et al. 2018); others worked on integrating blockchain technology into the information management systems to address several issues, such as quality control and provenance tracking (Sheng et al. 2020; Safa et al. 2019); and few researchers took aims at leveraging and/or integrating sensing techniques into the construction site and work process to facilitate information management (Ren and Zhang 2021b). To bridge this gap, the author developed a construction ontology to integrate construction site information with their corresponding data collection methods to provide recommendations regarding sensing technique selections, to support construction information management.

CHAPTER 3 – HETEROGENEOUS DATA ANALYSIS AT THE INFORMATION LEVEL

A portion of this chapter was previously published by:

“A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions.” *Advances in Civil Engineering*, *2021*.
https://doi.org/10.1155/2021/8824613

“Comparison of BIM Interoperability Applications at Different Structural Analysis Stages.” In *Construction Research Congress 2020: Computer Applications* (pp. 537-545). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784482865.057

“BIM Interoperability for Structural Analysis.” In *Construction Research Congress 2018: Construction Information Technology*.
https://ascelibrary.org/doi/abs/10.1061/9780784481264.046

3.1 Data Interoperability

3.1.1 BIM Application Phases/Functions Selection

At the information level, the BIM interoperability problem revolved around identifying information missing and information inconsistency between different data formats, platforms, and applications. This step defines two application phases/functions between which BIM interoperability will be studied. Example application phases/functions include architectural design, structural analysis, cost estimation, and energy simulation, among others.

BIM information is exchanged between different applications at different phases of a project. There are different types of BIMs for different applications at the design stage of a construction project, including architectural models, structural models, mechanical, electrical and plumbing (MEP) models, energy analysis models, and cost estimation models, among others. In this dissertation, the author selected two application tasks at the design phase - architectural design and structural analysis, because: (1) both applications belong to the design phase and therefore it is expected to be easier for collaboration to happen comparing to two application tasks that belong to different phases such as architectural design in the design phase and facility management in the operation phase; (2) the collaboration between architectural design and structural analysis is usually the first collaboration that happens in a project team; and (3) an effective collaboration between architectural design and structural analysis lays the foundation for other further collaborations (e.g., collaboration between architectural design and cost analysis) to succeed. Architectural design plays an essential role in creating the representational model (i.e., BIM) for a construction project (Penabad 2018). Structural analyses explore the various stresses, strains and displacements of the building elements. Currently it is easier to create a structural analysis model from scratch rather than adapting from the corresponding architectural model. A seamless information exchange between architectural design and structural analysis models could improve coordination effectiveness between architects and structural engineers and bring benefits in time and cost savings to the project team.

3.1.2 BIM-Based Information for Structural Analysis

Based on analysis regarding information need and provision for architectural design and structural analysis in the context of software usage purpose, the author summarized the following types of information needed in structural analysis/structural model: geometric information, loads information, material information, connection type information, and boundary conditions. Example types of information provided in architectural design/architectural model are: elevation and grids information, geometric information (e.g., interior/exterior wall, columns, doors, windows, floors, roofs, and stairs), and material information (e.g., material name, color and texture information).

Between information missing and information inconsistency, the author focuses on the information missing problem, because this problem originates from (and roots in) the information generation process, e.g., designer or the BIM authoring tool (information provider) did not include the information, rather than coming from proprietary software or processing algorithms. In contrast, information inconsistency is more of a software implementation problem. Therefore, the information inconsistency problem needs to be solved software by software whereas the information missing problem is possible to solve with automation and intelligent methods. According to Eastman et al. (2009), there are three information providers in BIM: designer, derived data, simulation or analysis. From model development perspective, material and geometric information are the essential parts of building elements based on above-mentioned analyses.

From the software point of view to support BIM-based structural analysis, different software platforms have different information coverage and different usage in the AEC industry.

How to import an IFC file and export it for further analysis successfully is another important consideration for interoperability. Table 2 summarizes different BIM software and their information coverage related to structural analysis (Zeng et al. 2014).

Table 2. Different BIM Software and Their Information Coverage (Zeng et al. 2014).

Software / Properties	Tekla Structures 18.1	Etabs 9	ArchiCAD 16	SAP 2000 v15	Revit Structure 2013	IFC 4 (newest version)
Geometric property	Yes	Yes	Yes	Yes	Yes	Yes
Material property	Yes	No	Yes	No	Yes	Yes
Structure analysis modeling	No	Yes	No	No	No	Yes
Load	No	No	No	No	No	Yes
Reinforcement information	Yes	No	No	No	No	Yes
Support restraint	No	No	No	No	No	Yes

From Table 2, we can see that different software cover different properties in their modeling. Therefore, when an IFC model is exported from one software and imported into another, certain information may miss or become untraceable. Redefining information manually is time-consuming and human error-prone. But without a full interoperability such manual input cannot be avoided. In the structural analysis domain, for example, when a shell element is being analyzed, the following information are needed but may not be successfully transferred using IFC models: new classes of load setting, combined material definition, different forces and moments (Wan et al. 2004). This requires direct support for IFC files and their processing in structural analysis software applications.

Even with direct IFC file support, missing information can still be a big problem in the importation/exportation of IFC files, especially those that are undetected (Kiviniemi 2008). To address this, developers have to manually check potential information loss before file exchange, or semi-automatically check it in order to avoid/reduce unknown information missing during the file exchange. Human-induced errors also need to be considered in such checking. The sizes and complexities of IFC models affect the importation/exportation process as well. Large models developed in more powerful platforms may contain information that is not directly interpretable in smaller platforms. One way to address this problem is to follow strict information requirements and MVDs to ensure the consistency of models across different platforms.

Experimental Analyses

To empirically test the interoperability of BIM for structural analysis, in this dissertation, the author initially conducted simple experiments using several structural analysis software as described in detail below.

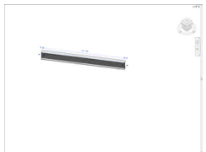
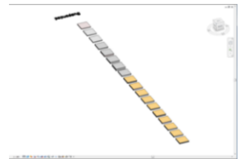
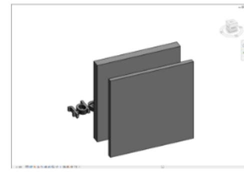
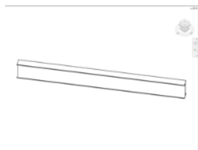
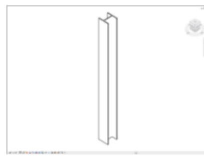
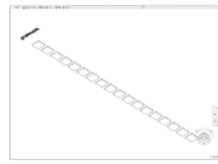
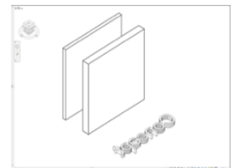
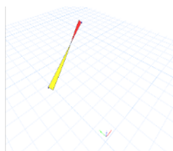
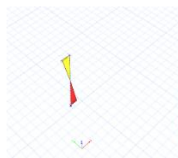
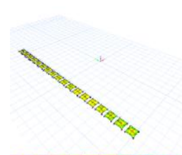
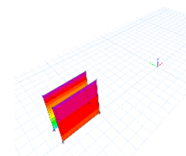
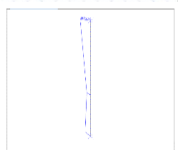
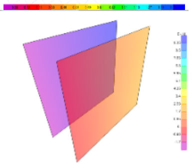
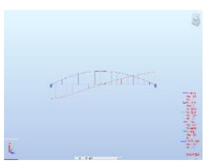
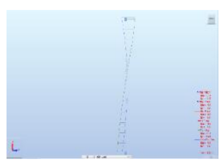
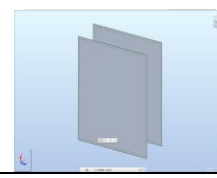
ETABS is a software that conducts linear structural analysis involving both static loads and dynamic loads (Kalny 2013). AutoCAD drawings can be imported directly into the ETABS software. Analysis in the ETABS software is based on spatial finite element analysis (FEA) and focuses on spatial features of the structure such as different earthquake zones for slabs. Objects are simulated by targeted geometric representations. Structural models can be transferred from IFC-based BIM to PKPM or YJK software, and further transferred to the ETABS software (Liu and Zhang 2015).

ABAQUS is a multi-function finite element software, especially suitable for non-linear analysis. It has a different type of database of material modeling comparing to other tools such as ETABS (with .e2k file) and SAP2000 (with .s2k file). For example, in ABAQUS, a structural model can be created directly by selecting material parameters in the graphical user interface (GUI). Then processes affecting the structure such as welding and post weld heat treatment of the structure can be automatically simulated and analyzed. It supports both modeling and structural analysis. Model upload from other software (e.g., Pro-Engineer, NX, and Solidworks) is also supported. IFC data exchange to ABAQUS software is possible by using PKPM or YJK as an intermediary platform (Liu and Zhang 2015). Input files for ABAQUS can be manually written to perform structural analysis. For example, ABAQUS reads material properties from input files using the following format: **MATERIAL, NAME=STEEL *ELASTIC 200. E9, 0.3*, meaning that this steel element has a Young's modulus of $200*10^9$ and a Poisson ration of 0.3.

SAP 2000 is designed by Computer and Structures Inc. in 2011. It is a civil engineering software used for designing and analyzing structural systems. It has built-in model templates, and advanced analysis options, especially for 3D complex space structures. SAP 2000 can also be used as a solver of other software, such as Tekla Structure software. Wind, wave, bridge and seismic loads can be automatically generated by integrated design code features (Fu 2015).

Autodesk Revit is part of the BIM software developed by Autodesk in 2014. It integrates many parts of different functions, such as architectural design, structural analysis, MEP engineering analysis, sustainability assessment and construction management support. Autodesk Revit Structure has many built-in architectural and structural templates. Models can be created from existing templates or by designing from scratch. In this dissertation, Autodesk Revit Structure software was used to create beam and column models for testing. Table 3 shows different types of files used in different software for the preliminary interoperability experiment, and their results of structural analysis.

Table 3. Different Types of Files in Different Software Representations.

Entities	1 Ifc Beam	1 Ifc Column	18 Ifc Slab	2 Ifc wall
Schema	IFC2X3			
Original file in Autodesk Revit 2018				
IFC file exported				
Structural analysis result in ETABS				
Structural analysis result in SAP2000				
Structural analysis result in Autodesk Robot				

In this experiment, Revit files were imported into Autodesk Revit, and exported as IFC files. The IFC files were imported into different software, such as ETABS, SAP 2000, and Autodesk Robot to conduct structural analysis. Four types of objects were used, namely, beam, column, slab, and wall. Beam and column models were created in Autodesk Revit Structure software directly, whereas slabs and walls models were downloaded from online sources. Table 4 shows the property representations of the models in different software for structural analysis, including material properties, section properties, degree of freedom, and load description.

IFC file was used as the standard file to test the interoperability between architectural design and structural analysis. During this import/export process, a few problems occurred and caused unsuccessful import/export results. For example, when IFC files were created in the Autodesk Revit Structure and imported into Autodesk Robot for structural analysis, material property was missing and loads information could not be loaded. Autodesk Revit Structure is good for processing large building models, but for simple models, such as a beam or column, boundary conditions such as a pin on certain point/node/element cannot be directly loaded. Secondly, when IFC files were imported, Autodesk Robot could not read material information from the IFC files. It caused information missing when IFC files were imported into Autodesk Robot. That was the reason why we had no structural analysis results for slab and wall (Table 3) when using Autodesk Robot. If Autodesk Robot can read IFC input files directly like ABAQUS as we explained above, the problem in loading forces information for the created models could be solved.

Table 4. Properties Representations in Different Software.

Software	Entities	Material Properties	Section Properties	Degree of Freedom	Load
ETABS	1Ifcbeam	Steel ASTM A992	Frame W12*26	UX UY RX RY	Trapezoidal
	1Ifccolumn	Steel ASTM A992	Frame W10*49	UZ RZ	Trapezoidal
	18Ifcslabs	nbl_DeckBeamAndBlock150	Slab nbl_DeckBeamAndBlock150	UZ RZ	Uniform $2kN/mm^2$
	2Ifcwalls	nbl_concept	Wall nbl_concept150.000	UY UZ RY RZ	Uniform $2kN/mm^2$
SAP2000	1Ifcbeam	Steel ASTM A992	Frame W12*26	UX UY RX RY	Trapezoidal
	1Ifccolumn	Steel ASTM A992	Frame W10*49	UZ RZ	Trapezoidal
	18Ifcslabs	nbl_DeckBeamAndBlock150	Slab nbl_DeckBeamAndBlock150	UZ RZ	Uniform $2kN/mm^2$
	2Ifcwalls	nbl_concept	Wall nbl_concept150.000	UY UZ RY RZ	Uniform $2kN/mm^2$
Autodesk Robot	1Ifcbeam	Steel ASTM A992	Frame W12*26	UX UY RX RY	Trapezoidal
	1Ifcolumn	Steel ASTM A992	Frame W10*49	UZ RZ	Trapezoidal

Table 5 compares different software from a user's perspective through a small comparative experiment. ETABS and SAP 2000 turned out to be easier to learn and use, whereas Autodesk Robot is more complex but more powerful.

Table 5. Advantages and Disadvantages of Different Software.

Software	IFC Import	Time Consumed	Feasibility	Comment
ETABS	Yes	10 minutes	Properties need to be set manually, it may cause human error	Autodesk Robot is more complicated to use than ETABS and SAP 2000, it is not an analysis solver, but it has good compatibility with design software to import model structure quickly
SAP 2000	Yes	10 minutes	Properties need to be set manually, it may cause human error	
Autodesk Robot	Yes	20 minutes	Material properties may be missing when importing IFC models	

3.1.3 IFC-Based Material Signatures for BIM Applications

The author argues that the information provider of the material information should be the designer/architect during the architectural design phase, either directly or indirectly together with geometric information of building objects for further use (e.g., structural analysis). Geometric information has been well studied in literature, and material information representation and analysis is identified as a gap (Ramaji and Memari 2018; Sacks et al. 2010). To support material information representation and coverage in the context of BIM applications, the author analyzed selected AEC software in terms of their material property settings in IFC-based BIMs (Table 6), which is a necessary step in both architectural design and structural analysis. In some software, materials can be selected directly, such as Solidworks, which however is not specifically designed for civil structural analysis. In some software, only limited materials can be selected, for example, Graytec Advanced and SCIA software only include steel, concrete, and timber materials. Although some FEA software, such as ANSYS and ABAQUS, have been widely used for structural analysis, they have certain limitations when used for civil structural analysis. For example, they can only be used to analyze small structures. In addition, the graphical user interface and application programming interface of FEA software need improvement in terms of information representations in civil engineering to be better used for civil structural analysis purpose (Fu 2015; Deng and Chang 2006).

Table 6. Material Property Setting in Different Software.

Software	Software Type	Choose Material Directly	Define New Material	Comments
Tekla Structure	Structural	√		
Autodesk Revit Structure	Structural	√		Beside materials, it also contains graphics, appearance, physical, and thermal properties.
ETABS	Structural	√	√	
SAP 2002	Structural	√	√	
Graytec Advanced	Structural	√		Only cover steel, concrete, and timber materials.
SCIA	Structural	√		If the material names in an IFC file are not in accordance with code names, it is necessary to define a material conversion table in the Import dialogue.
CypeCAD	Structural	√		Only cover steel, concrete, composite steel and concrete, and timber.
STAAD	Structural	√	√	
PKPM	Structural	√		The menu provides the diagram and calculation results of model rich graphics, and a template and reinforced material list.
MIDAS	Structural	√	√	Cover concrete, steel, wood and other types of material that a user defined.
ArchiCAD	Architectural	√	√	
ANASYS	FEA	√	√	
ABAQUS	FEA	√	√	
Solidworks	Engineering Design	√	√	Concrete material parameters could not be defined.

To successfully represent material information in the BIMs, the author analyzed the needed material information in different analysis scenarios and summarized the needed material properties in each scenario into the author's developed invariant material signature: mass, cross-sectional area, volume, mass density, stress, strain, shear stress, shear strain, shear modulus, Young's modulus, thermal expansion coefficient, and Poisson's ratio (Aldegeily et al. 2018). Based on the proposed material signature concept, the author developed invariant material signatures for three main types of materials – steel, concrete, and wood. Figure 3 illustrates the detailed properties of these invariant material signatures.

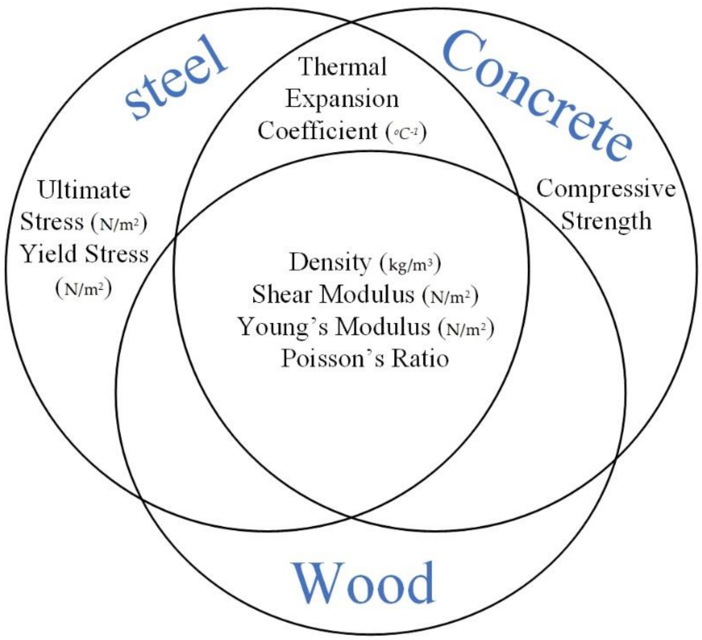


Figure 3. Material signature for different material types.

3.1.4 BIM Usage in Three Different Structural Analysis Stages

Although the existing work analyzed the BIM applications for structural analysis from different perspectives, they did not focus on detailed analysis stages of a structural analysis process. To address this gap, the author analyzed the use of BIM in three different structural analysis stages (intrinsic, extrinsic, and analysis stages) through investigating both the exported text files and the corresponding exported IFC files from structural analysis BIM tools to find potential missing information. In this section, the same structure was created in two structural analysis BIM software – Software A and Software B, which were used to export model information into text files and IFC files, respectively. The information coverage in all the three stages for both types of files were analyzed in a four-step research methodology. Step 1: Define Structural Analysis Stages - This step defines three structural analysis stages in which BIM information coverage will be studied. Step 2: Analyze Exported Text Files of Different Analysis Stages – This step analyzes three different structural analysis stages in their exported text files from a structural analysis BIM software, which construes a horizontal discussion of information coverage (i.e., compares and analyzes information coverage in the same type of file at three different stages). Step 3: Analyze Exported IFC Files of Different Analysis Stages – This step analyzes three different structural analysis stages in their exported IFC files from a different structural analysis BIM software comparing to Step 2, which is also a horizontal discussion similar to Step 2. Step 4: Compare Exported Text Files and IFC Files in Information Coverage – This step comparatively analyzes information coverage between text files and corresponding IFC files which are converted from proprietary BIMs, which construes a vertical discussion of information coverage (i.e., compares and analyzes information coverage between different types of files).

Step 1: Define Structural Analysis Stages

Structural analysis integrates a set of mechanics theories that follow the physical laws to predict the behavior of a structure under different types of analysis scenarios (Kuang-HuaChang 2015). A typical structural analysis process runs as follows: (1) create geometric information and assign material information to each element; (2) set supports information and define load information; and (3) run structural analysis and report the result. In this dissertation, the author proposed the division of the structural analysis process into three stages: intrinsic stage, extrinsic stage, and analysis stage (Figure 4). At the three different structural analysis stages, geometric and material information, supports and load information, and structural analysis results are represented, respectively.

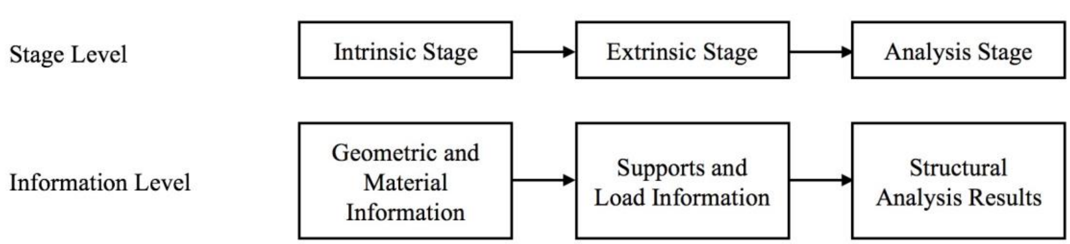


Figure 4. Three structural analysis stages.

Step 2: Analyze Exported Text Files of Different Analysis Stages

In this dissertation, a simple structure was used, which contained four beams and four columns (Figure 5) to analyze the information in the different text files at the three stages: (1) a text file of BIM model with geometric and material information only, (2) a text file of BIM model with supports and load information added, and (3) a text file of BIM model with structural analysis results further added (Figure 6). However, the structural analysis results could not be exported from Software A [Figure 6(c)], which shows the information missing problem when exporting text files from Software A at the analysis stage. Only the geometric, material [highlighted in the Figure 6(a)], supports [highlighted in the Figure 6(b)] and load information [highlighted in the Figure 6 (b) (c)] could be exported to text files from Software A.

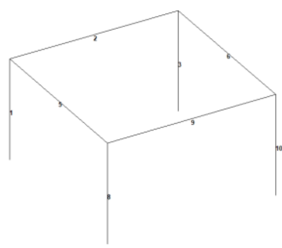
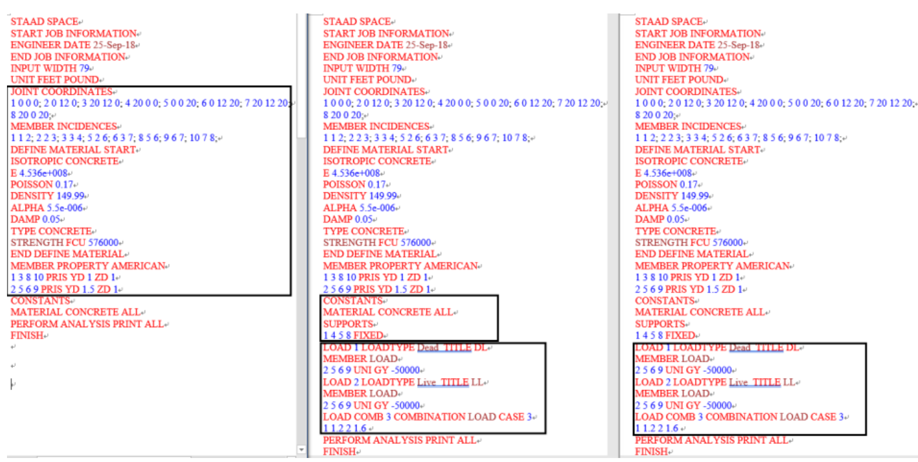


Figure 5. A simple beam-column structure in Software A.



(a) Intrinsic Stage (b) Extrinsic Stage (c) Analysis Stage

Figure 6. Text files exports of Software A at three stages.

Step 3: Analyze Exported IFC Files of Different Analysis Stages

IFC-based BIMs enable the information integration and representation of the different application models to support BIM interoperability. In this step, the same BIM model was created in Software B which had been created in Software A in Step 2, to analyze information coverage in the three structural analysis stages. Figure 7 shows the partial IFC file exported from Software B at the extrinsic stage. In the IFC file, the geometric and material information can be mainly defined by “IfcCartesianPoint” and “IfcMaterial” entity instances, respectively (Figure 7). Load information can be represented by “IfcRelAssignsToGroup” entity instance to assign load information to different elements in the structure (Figure 7). After comparing the IFC files at the three stages, only the geometric, material, supports and load information could be exported to IFC files from Software B. Structural analysis results could not be exported to IFC file based on the IFC data analysis. There is an information missing problem when exporting the IFC file from Software B at the analysis stage.

```
#28=IFCDERIVEDUNIT((#59,#60),.PLANARFORCEUNIT.,$);
#29=IFCDERIVEDUNIT((#61,#62,#63),.LINEARMOMENTUNIT.,$);
#30=IFCDERIVEDUNIT((#64,#65),.SHEARMODULUSUNIT.,$);
#31=IFCDERIVEDUNIT((#66,#67),.MODULUSOFELASTICITYUNIT.,$);
#32=IFCCONVERSIONBASEDUNIT(#68,.THERMODYNAMICTEMPERATUREUNIT.,'FAHRENHEIT',#69);
#33=IFCDERIVEDUNIT((#70),.THERMALEXPANSIONCOEFFICIENTUNIT.,$);
#34=IFCACTORROLE(.STRUCTURALENGINEER.,$,$);
#35=IFCACTORROLE(.MANUFACTURER.,$,$);
#36=IFCCARTESIANPOINT((0.0000000E+000,0.0000000E+000,0.0000000E+000));
#145=IFCMATERIAL('4000Psi');
#146=IFCPROPERTYSINGLEVALUE('CompressiveStrength',$,IFCPRESSUREMEASURE(5.7600000E+005),#26);
#147=IFCPROPERTYSINGLEVALUE('MassDensity',$,IFCMASSDENSITYMEASURE(4.6621422E-003),#23);
#148=IFCPROPERTYSINGLEVALUE('PoissonRatio',$,IFCRATIOMEASURE(2.0000000E-001),$);
#149=IFCPROPERTYSINGLEVALUE('ShearModulus',$,IFCSHEARMODULUSMEASURE(2.1629979E+005),#30);
#150=IFCPROPERTYSINGLEVALUE('ThermalExpansionCoefficient',$,IFCTHERMALEXPANSIONCOEFFICIENTMEASURE(5.5000000E-006),#33);
#151=IFCPROPERTYSINGLEVALUE('YoungModulus',$,IFCMODULUSOFELASTICITYMEASURE(5.1911950E+005),#31);
#239=IFCRELASSIGNSTOGROUP('2tkthNk51E6Q1jvYPeKS6h',#3,$,$,(#84,#101,#106,#111,#116,#121,#126,#131,#136,#157,#165,#173,#181,#197,#211,#225),.PRODUCT.,#92);
#240=IFCRELASSIGNSTOGROUP('1bLU62PwfDA8Oz0518f1MP',#3,$,$,(#191,#205,#219,#233),.PRODUCT.,#85);
#241=IFCRELASSIGNSTOGROUP('1Ci8A IBD6DPCiUtomarVM',#3,$,$,(#192,#206,#220,#234),.PRODUCT.,#87);
```

Figure 7. An example partial IFC file exported from Software B.

Step 4: Compare Exported Text Files and IFC Files in Information Coverage

The author compared information transfer by exported text files and IFC files from different BIM analysis software of the same BIM model from the horizontal comparison perspective in Step 2 and Step 3, respectively. In the current step, the author compared the information coverage between text files and corresponding IFC files from the vertical comparison perspective and found that: (1) the text file was more concise than the corresponding IFC file of the same model. For instance, in the text file, material property definitions were represented straightforwardly in the highlighted content in Figure 6(a), e.g., E and POISSION represented Young’s Modulus and

Poisson Ratio of material properties, respectively. In the IFC file, material properties were represented by “IfcPropertySingleValue” entity instance. The property name and numerical information were defined by the “Name” and “NominalValue” attributes of an “IfcPropertySingleValue” entity instance, e.g., IFCPROPERTYSINGLEVALUE('PoissonRatio',$,IFCRATIOMEASURE(2.0000000E-001),$). The “Name” attribute was defined by the string “'PoissonRatio'”. The “NominalValue” attribute was represented by “IFCRATIOMEASURE(2.0000000E-001)” (Figure 7). (2) The function of importing and exporting text files was not available in all BIM analysis software. The text files exported from different BIM analysis software were also different. Different BIM analysis software can only read specific text files generated by themselves. It is a software-dependent and text-file-function-dependent method to transfer data. (3) The IFC file contains more reference information than the corresponding text file. For example, the IFC file has its own format structure to define Unit information in the model (Figure 8). The unit is consisted of two parts - the representation of unit format is A*B, e.g., the unit of mass density will be represented by (kilogram ^ 1) * (millimeter ^ -3). In contrast, the text file export did not contain unit information of material, only numerical information was found.

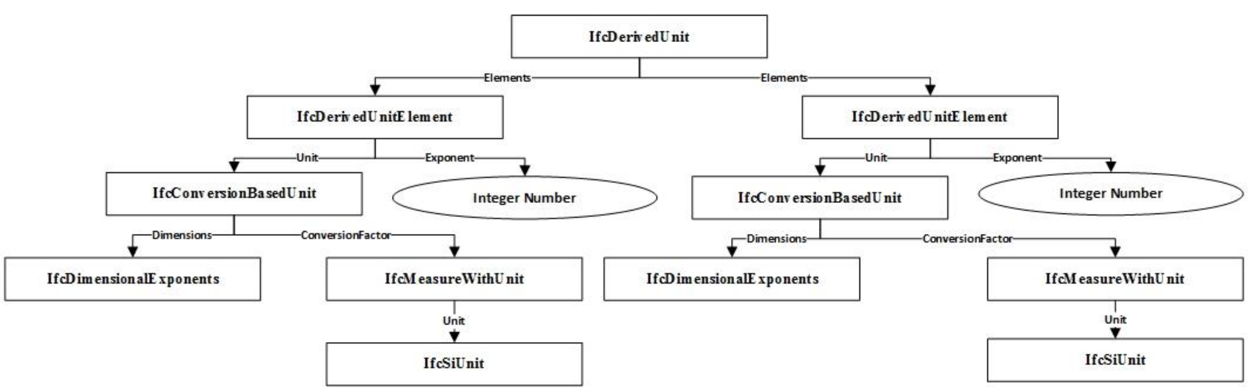


Figure 8. IFC format structure of defining unit information in the model.

Information coverage analysis results are shown in Table 7. Only structural analysis results could not be exported to the test file from Software A and IFC file from Software B. Geometric, material, supports, and load information could be exported both to the text and IFC files. Intrinsic stage was the first step to conduct structural analysis. At the intrinsic stage, geometric and material information were added to the model as the input. All the information elements (i.e., geometric and material information elements) could be exported from Software A & B. Extrinsic stage was the second step to conduct structural analysis. At the extrinsic stage, supports and load information were added on top of the model at the intrinsic stage. All the information elements (i.e., geometric, material, supports, and load information elements) could be exported from Software A & B. Analysis stage was the third step to conduct structural analysis, at the analysis stage, structural analysis was conducted in the BIM analysis software based on the model at the extrinsic stage. Structural analysis results would be represented by Von Mises stress, axial force, and torsion structural analysis results. However, the structural analysis results could not be exported from BIM analysis software neither to the text file nor to the IFC file.

Table 7. Information Coverage Analysis.

Information Coverage	Geometric and Material Information	Geometric, Material, Supports and Load Information	Geometric, Material, Supports, Load Information and Structural Analysis Results
Stages	Intrinsic Stage	Extrinsic Stage	Analysis Stage
Text File	√	√	Missing Structural Analysis Results
IFC File	√	√	Missing Structural Analysis Results

To explain the information coverage among the three structural analysis stages, the author proposed a new stage, information, and file (SIF) system model (Figure 9). The system model includes three different implementation levels: stage level, information level, and file level. The stage level provides structural analysis stages, which are intrinsic, extrinsic, and analysis stages. Each stage contains different types of structural analysis information, i.e., intrinsic stage contains intrinsic property information of a structure, extrinsic stage contains extrinsic information to be added during the structural analysis, and analysis stage further adds analysis results. Information level indicates the required information in the BIMs for structural analysis, they are geometric and material information, supports and load information, and structural analysis results information. Different types of information are required in different structural analysis stages, e.g., geometric and material information is required in all three analysis stages, supports and load information is required at the extrinsic and analysis stages. All types of information except structural analysis results information need to be manually input or transferred from other models when structural analysis is performed. The file level contains text, IFC, and other types of files of the BIM information between which information coverage analysis can be studied. The stage level defines required information for the information level, and the information level instantiates the definitions of different stages. Information level analysis is based on the different types of files at the file level, and the different files at the file level carry the required information at the information level. The three levels are interconnected in the system.

The stages analysis system is consisted of three levels, which contains the main paths of information transfer during a structural analysis process. The solid arrows represent solid connections between two levels, the dashed arrows represent questionable connections. For example, the dashed arrows between information level and file level show that structural analysis results currently cannot be exported neither to the text file nor to the IFC file from BIM analysis software. Each stages analysis path will be consisted of three blocks from the three different levels that are connected through two arrows. The analysis of information coverage among other types of files is out of the scope of this dissertation.

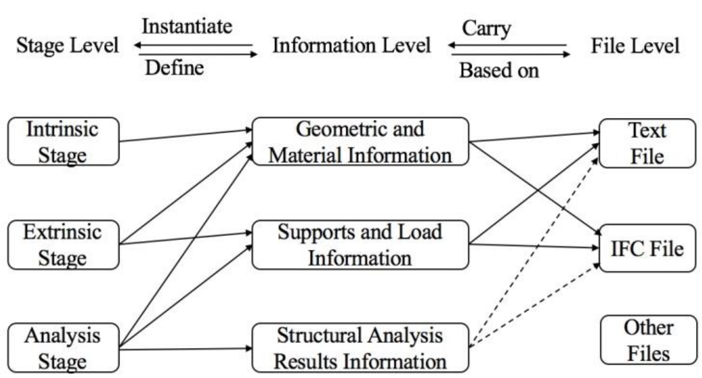


Figure 9. Stage-information-file (SIF) system.

3.2 Data Analyses and Management

3.2.1 BPMN Generation to Support BIM Interoperability

The author analyzed the information transfer and communication between architectural design and structural analysis applications and summarized a BPMN that describes steps for creating an architectural model and a structural model, with information exchange between the two models (Figure 10). Solid line arrows represent step sequences for model creation processes. Dashed lines show information transfer between different steps or models. Information from earlier steps in each model will be saved and delivered to its following steps. The shaded area (i.e., create architectural columns - create doors - create windows - create floors - create ceilings - create stairs) in the process of creating an architectural model represents composite sub-processes, where detailed components of an architectural model are developed. A structural model will be created based on the information from an architectural model, such as geometric information and material information. For example, walls and roofs from an architectural model provide geometric information that can be used as references in the creation of the corresponding structural model. The first step in the process of creating a structural model is a composite sub-process, which includes simplifying geometric information and maintaining material information from an architectural model. For example, a beam or column is represented by simplifying its geometry into a straight line in the structural model without losing beam or column material features. The other information not readily transferred from the architectural model is then added. The nodes connection information is shown by points in the structural model while specifying the connection types. Geometric information and material information will be saved and delivered to later steps. Material parameters may need to be inputted manually to conduct structural analysis. An "envelope" symbol represents the overall message flow between an architectural model and a structural model. The BPMN represents the information transfer between different models and demonstrates that the intrinsic information of an architectural model can be the extrinsic information of a corresponding structural model (e.g., material information), which reflects potential BIM interoperability problem at the information level. The two model-development processes are usually conducted in different software by different personnel. An efficient information exchange between the architectural software and structural software and between the architect and structural engineer is therefore important.

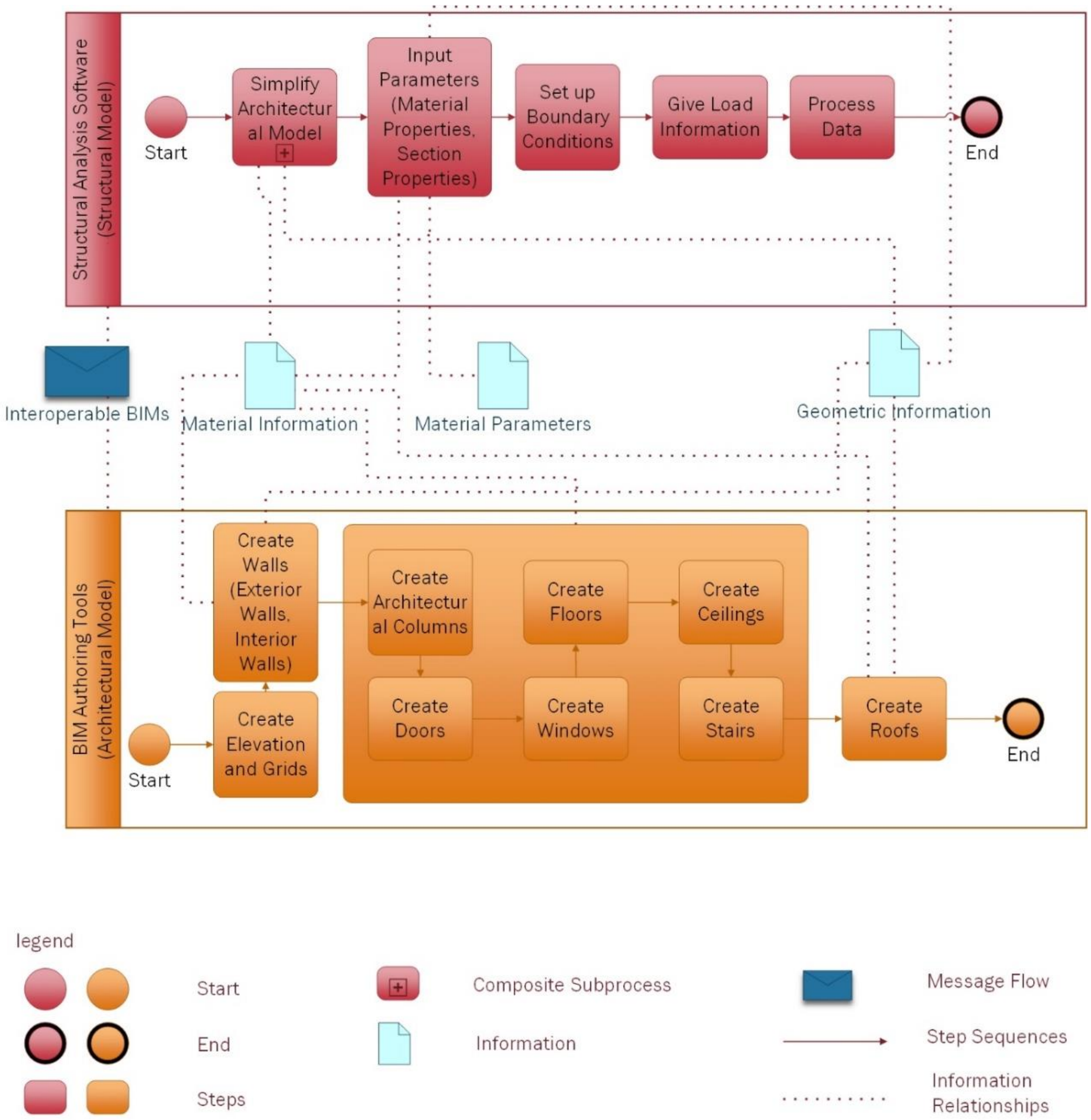


Figure 10. A BPMN representation of geometric and material information transfer.

3.2.2 Technical Routes Analysis for BIM Interoperability Management

Based on analysis of recent literatures regarding BIM interoperability between architectural model and analysis model from technical and process perspectives (Table 8), it was found that most of existing research only focused on developing roadmaps from technical perspective, for example, developing software tools, system architectures, and information transfer mechanisms to support interoperable BIM applications (Ramaji and Memari 2018; Ren et al. 2018;

Sanguinetti et al. 2012; Yang and Zhang 2006). Other researchers solely focused on collaboration and integration framework of AEC projects to improve BIM interoperability (Solnosky et al. 2014; Grilo and Jardim-Goncalves 2010; Bank et al. 2010). There is a lack of systematic investigations in solving the information transfer problems from the technical dimension in the context of the process dimension to support BIM interoperability. To address the BIM interoperability issue that is initiated from the technical dimension in the context of the process dimension, the author identified and proposed the following six technical route segments of interoperability between architectural design and structural analysis (Figure 11). A route for BIM interoperability would be a combination of one or more route segments to form a closed loop for information transfer. For example, 1-4-3 is one such technical route where information can be directly transferred from a proprietary architectural BIM to a proprietary structural analysis model, then structural analysis model can be exported to IFC and read back to the proprietary architectural BIM platform. To illustrate that, an architectural model can be developed and saved in an architectural design software (e.g., Autodesk Revit), in which the information could be directly read by a compatible structural analysis software (e.g., Autodesk Robot), then the structural analysis model that is developed based on the information from the architectural model can be saved and exported as an IFC model, which can be read back to the architectural software. In this process, for instance, the dimensional information of a beam element in the architectural model can be transferred as values of x, y, and z coordinates to the corresponding developed structural analysis model, then the dimensional information in the structural analysis model can be exported as an entity instance "IfcCartesianPoint" in an IFC file, which can be imported and read back as dimensional information to an architectural design software (e.g., Autodesk Revit).

Table 8. Sample Work on BIM Interoperability between Architectural Model and Analysis Model from Technical and Process Dimensions.

Literature	Main Contribution	Technical Dimension	Management Dimension
Ren et al. 2018	Tested BIM interoperability in structural application among different AEC software and found information missing and information inconsistency issues among BIM models	Yes	No
Ramaji and Memari 2018	An interpreted information exchange mechanism of IFC-based BIMs for information transformation from BIM design models to BIM application models	Yes	No
Aldegeily et al. 2018	Analyzed the interoperability between architectural design and structural analysis.	Yes	No
Hu et al. 2016	A method that combined IFC-based BIM conversion algorithms to convert architectural models to structural models while overcoming inconsistencies in data structures to improve BIM interoperability	Yes	Yes
Solnosky et al. 2014	Recommendations for BIM interoperability from the modular construction perspective.	No	Yes
Steel et al. 2012	Presented issues in visualization for IFC-based BIM interoperability.	Yes	No
Sanguinetti et al. 2012	Integrated modeling and application interfaces to architectural design and specific analysis.	Yes	No
Grilo and Jardim-Goncalves 2010	Addressed the interaction type and geographic range needs for BIM interoperability at the management level.	No	Yes
Bank et al. 2010	A *Decision-Making* tool and sustainability metrics to improve data sharing among various building models.	No	Yes
Sacks et al. 2010	A CAD workflow for precast façade design to help BIM data exchange and use in project collaboration.	Yes	Yes
Yang and Zhang 2006	A new semantic approach to improve interoperability between BIMs and semantic model data.	Yes	No

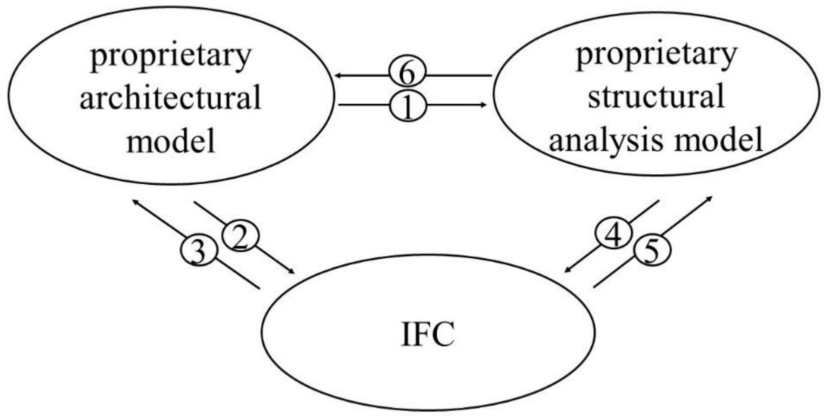


Figure 11. Six technical route segments of interoperability between architectural design and structural analysis.

In project delivery methods CMR and IPD, because the built-in collaboration enables architects and structural engineers to work together with other stakeholders as one team. The communication and negotiation between them and with the owners at an early stage of a project makes it possible to identify/select architectural and structural software to use, so that Route 1-6 become possible. For example, because the architects and structural engineers could work together to select the compatible software both for architectural design and structural analysis (e.g., Autodesk Revit/Robot). In this process, a developed architectural model could be saved as a DWG (AutoCAD Drawing) format model and imported directly into the analysis software for structural analysis. In project delivery methods DBB and CMMP, because the owner or owner's representative establishes contracts with the different stakeholders separately, it is more difficult to specify compatible architectural or structural software to use for the architects and structural engineers, therefore the Route 2-5 is more feasible. For example, an architectural model created by an architect could be saved and exported to IFC format. Structural engineer could import the IFC file into structural analysis tool to get the information (e.g., geometric information and material information) to conduct further analysis. In this process, the exported IFC file can be a bridge between architectural model/architectural design and structural model/structural analysis to support information transfer for interoperable BIM applications. For project delivery method DB and CMA, although the owner does not hold all contracts individually and directly, the Route 2-5 is still feasible. Therefore 2-5 could be a potential solution for all project delivery methods if the quality of information transfer in this route can be guaranteed.

From the process dimension, in different project delivery methods, the architects and structural engineers may choose software that may or may not be directly interoperable. Different interoperability scenarios will affect the possible technical routes to be used. For example, Route *1-6* (i.e., proprietary architectural model -> proprietary structural analysis model -> proprietary architectural model) become possible if the negotiations between architects and structural engineers and with the owners at an early stage of a project identify selected architectural and structural software to use. In the Route *1-6*, compatible software platforms provide proprietary channels to enable information and model transfer, but the limitations regarding material information missing and inconsistency still need to be addressed (Table 6). Otherwise, the Route *2-5-4-3* (i.e., proprietary architectural model -> IFC -> proprietary structural analysis model -> IFC -> proprietary architectural model) is more feasible. In the Route *2-5-4-3*, IFC model works as an intermediate data representation to support information and model transfer, which provides a new way to bridge architectural design and structural analysis tasks at the design phase.

The proposed material information representation method (i.e., the invariant material signatures) can be implemented for both Route *1-6* and Route *2-5-4-3*. The author further leveraged technical BIM interoperability Route *2-5-4-3* to develop an IFC-based implementation, as providing solutions to direct information transfer between proprietary software (i.e., Route *1-6*) has to be conducted by the corresponding software companies. Similarly, the information inconsistency problem also has to be addressed by corresponding software companies even if an IFC-based workflow is used, by refining their exportation/importation to/from IFC or other formats to make sure it is error-free.

CHAPTER 4 – HETEROGENEOUS DATA REFINING AT THE PROCESS LEVEL

A portion of this chapter was previously published by:

“A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions.” *Advances in Civil Engineering*, *2021*. https://doi.org/10.1155/2021/8824613

“Model Information Checking to Support Interoperable BIM Usage in Structural Analysis.” In *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation* (pp. 361-368). Reston, VA: American Society of Civil Engineers. : https://doi.org/10.1061/9780784482421.046

“Semantic Rule-Based Construction Procedural Information Extraction to Guide Jobsite Sensing and Monitoring.” *Journal of Computing in Civil Engineering*, 35(6), 04021026. DOI: 10.1061/(ASCE)CP.1943-5487.0000971.

“Enhancing Interoperable BIM Applications with Invariant Signatures of AEC Objects - A Case Study on Structural Analysis of a High-Rise Building Model.” (In Preparation)

4.1 Information Representation and Checking for BIM Application

4.1.1 An Invariant Signature-Based Information Representation Method

Invariant signatures of an AEC object are “a set of intrinsic properties of the object that distinguish it from others and that do not change with data schema, software implementation, modeling decisions, and/or language/cultural contexts” (Wu et al. 2021). This section focuses on information missing and information inconsistency analysis (i.e., gap analysis) during the information transfer between different phases/functions based on data analysis, and identifies information representation needs for IFC-based BIM interoperability. An IFC file not only contains geometric information of building elements, such as beams, columns, slabs, and walls, but also contains attributes for each object describing their physical and functional properties such as material properties and occupancy types. Figure 12 shows an example of a partial IFC file. In Figure 12, each line is representing an IFC entity, and each argument in the parenthesis represents an attribute of this entity. For example, line #80 is one entity in the IFC file that represents material properties. In this entity, “#80” is its data line number, and “IfcExtendedMaterialProperties” is the name of the entity. “STD-Concrete” is one attribute value that is representing the name of an associated material. Material information such as material name can be extracted from such entities in the IFC physical file through analysis of a building element. For example, an “IfcBeam” can be linked to its related material entity (i.e., “IfcMaterial” in IFC file), which can be further related to other entities using “IfcRelAssociatesMaterial” object (Liebich 2013). Detailed material properties in the IFC files are defined by the entity “IfcPropertySingleValue.” There are four attributes of “IfcPropertySingleValue”: “Name,” “Description,” “NominalValue,” and “Unit.”

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION (('ViewDefinition [CoordinationView]'), '2;1');
FILE_NAME ('Model 1 updated xz diaphragm p delta.ifc','2015-09-01T01:05:39',('Miqdad'),('gg'),'15.2.2','ETABS 2015','None');

FILE_SCHEMA(('IFC2X3'));
ENDSEC;

DATA;
#1=IFCRELAGGREGATES('0nViTsTdvAih6qtPD70Hxd',#3,$,$,#4,(#5));
#2=IFCRELAGGREGATES('1ZBISaGP5AAuDmjUWsOILr',#3,$,$,#5,(#6));
#3=IFCOWNERHISTORY(#7,#8,$,.NOCHANGE.,1441069539,$,$,1441069539);
#4=IFCPROJECT('0bepq99WH6SPBtaUQvpxcj',#3,'Model 1 updated xz diaphragm p delta.$et',$,$,$,$,(#9),#10);
#5=IFCSITE('3dLvXUwrbB7Q9q0FWDCaP$',#3,'Default Site',$,$,$,$,$,.ELEMENT.,$,$,$,$,$);
#6=IFCBUILDING('0pYH7FsGP18gLYtfcLzLR8',#3,'Default Building',$,$,$,$,$,.ELEMENT.,$,$,$);
#7=IFCPERSONANDORGANIZATION(#11,#12,$);
#8=IFCAPPLICATION(#13,'15.2.2','ETABS 2015','ETABS 2015');
#9=IFCGEOMETRICREPRESENTATIONCONTEXT('Project World','Model',3,$,#14,$);
#79=IFCCOLUMN('3zWBvyzd5BgQ6Z_5Mwz1J1',#83,'1',$,$,#84,#85,$);
#80=IFCEXTENDEDMATERIALPROPERTIES(#86,(#87,#88,#89,#90,#91,#92),$,'STD-CONCRETE');
#81=IFCRELASSOCIATESMATERIAL('03Qf12zgj5eBwGF3FEEjJP',#3,$,$,(#79),#86);
```

Figure 12. Sample IFC entities representation.

Figure 13 shows a material property representation implementation diagram of a 12-storey building model in IFC, which was tested in the case study (Figure 19). It shows that in this IFC file, any information related to material properties is rooted in an “IfcExtendedMaterialProperties” entity. There are four directly related entities which are “IfcMaterial,” “IfcPropertySingleValue,” “IfcText” and “IfcLabel” to represent material property details. There are four different types of material properties representations (attributes) in the entity of “IfcPropertySingleValue,” they are “IfcIdentifier,” “IfcText,” “IfcValue,” and “IfcUnit,” which represent material name, material description, nominal value of material property, and unit of value, respectively. Through the proposed invariant material signatures, IFC representation could represent material information in both the architectural model and the structural model in a consistent way.

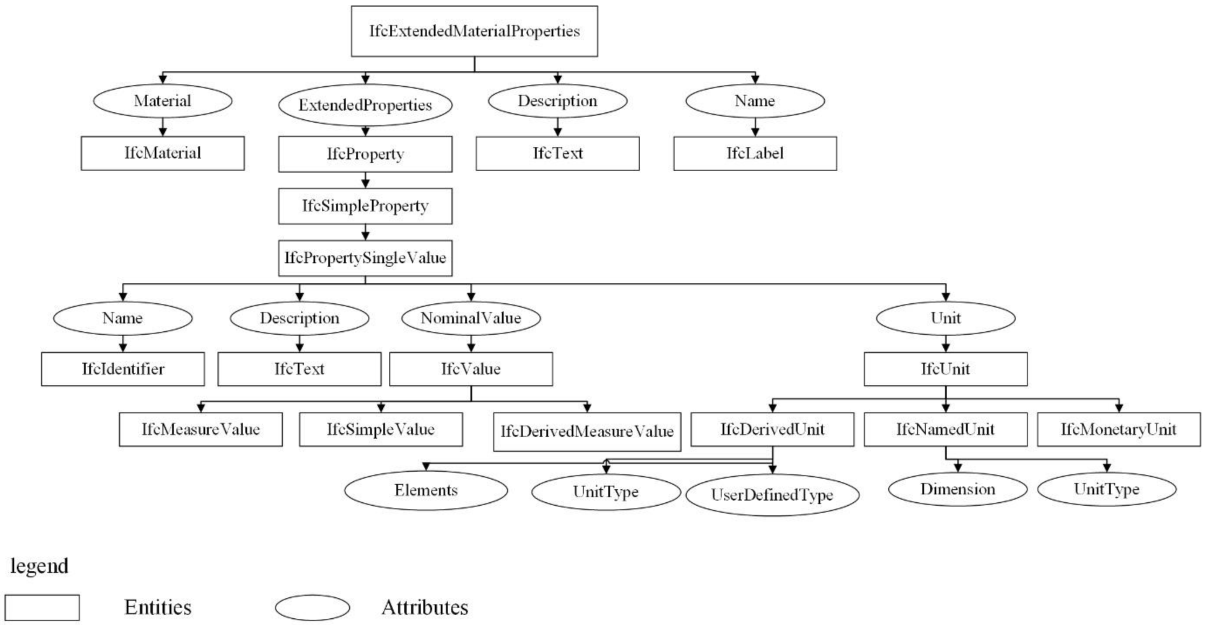


Figure 13. Common material property representation based on IFC schema.

The author analyzed IFC model regarding material information representation implementation in two versions: IFC2X3 and IFC4, and developed corresponding MVDs in IfcDoc software (Liebich 2013). Attributes of the same entity (e.g., "IfcMaterialProperties") could be different between the two versions, e.g., in the IFC2X3 version, only the attribute "Name" is included in the "IfcMaterialProperties," whereas in the IFC4 version, it has "HasExternalReferences," "Name," "Description," "Properties," and "Material," five attributes in total. There is no relationship between attributes of the "IfcPropertySingleValue" entity and the "IfcMaterialProperties" entity in the IFC2X3 version, whereas in the IFC4 version, attribute "Properties" is the connection between the "IfcPropertySingleValue" entity and the "IfcMaterialProperties" entity (Figure 14 and Figure 15). However, information from these different versions of IFC could all converge in our invariant material signatures.

Furthermore, because IFC2X3 version has its limitations for model representation, some of the entities could not be used in the IFC2X3 version (Figure 16). As Figure 16 shows, some entities such as "IfcExtendedMaterialProperties" could not be defined in the IFC2X3 or IFC4 versions. Some entities such as "IfcMaterialProfile" and "IfcMaterialDefinition" could not be defined in the IFC2X3 version but could be defined in the IFC4 version. Its structure and relationships were also different from the IFC4 version. For example, there were three attributes

“Name,” “HasRepresentation,” and “ClassifiedAs” for the entity “IfcMaterial” in the IFC2X3 version. But there were nine attributes “AssociatedTo,” “HasExternalReferences,” “HasProperties,” “Name,” “Description,” “Category,” “HasRepresentation,” “IsRelatedWith,” and “RelatesTo” for the entity “IfcMaterial” in the IFC4 version. Based on the structure of IFC4, it could represent more information because it incorporated more abundant entity attributes than IFC2X3.

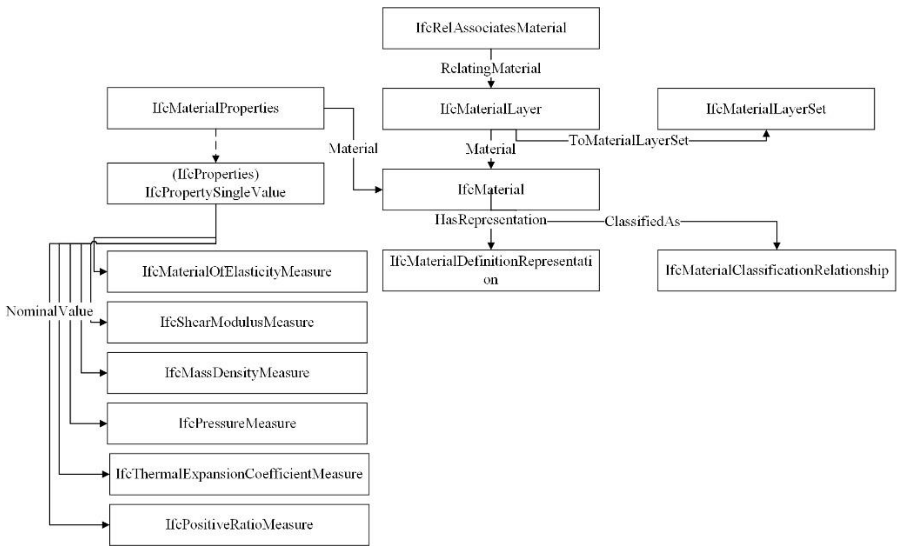


Figure 14. Structure of the IFC2X3 version of MVD.

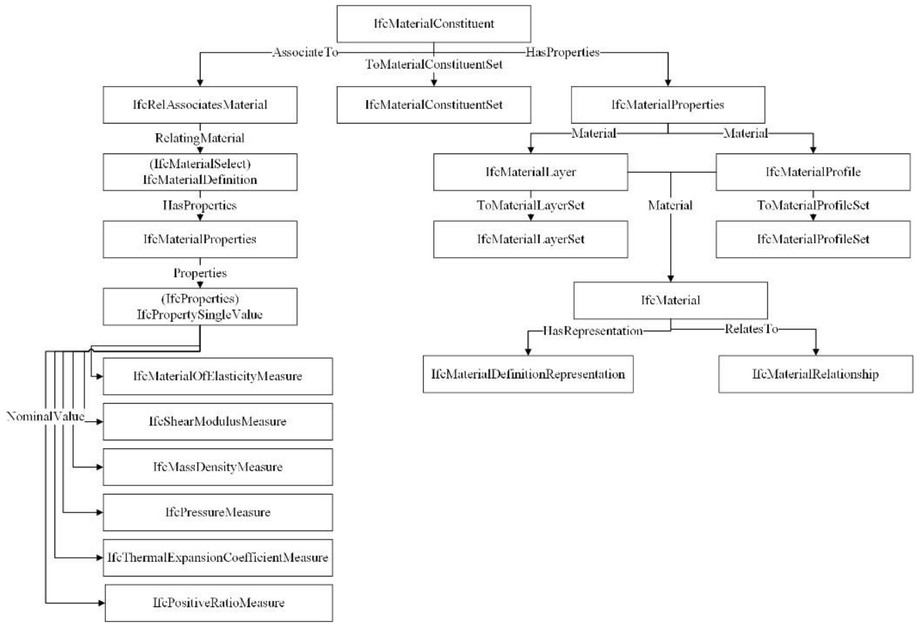


Figure 15. Structure of the IFC4 version of MVD.

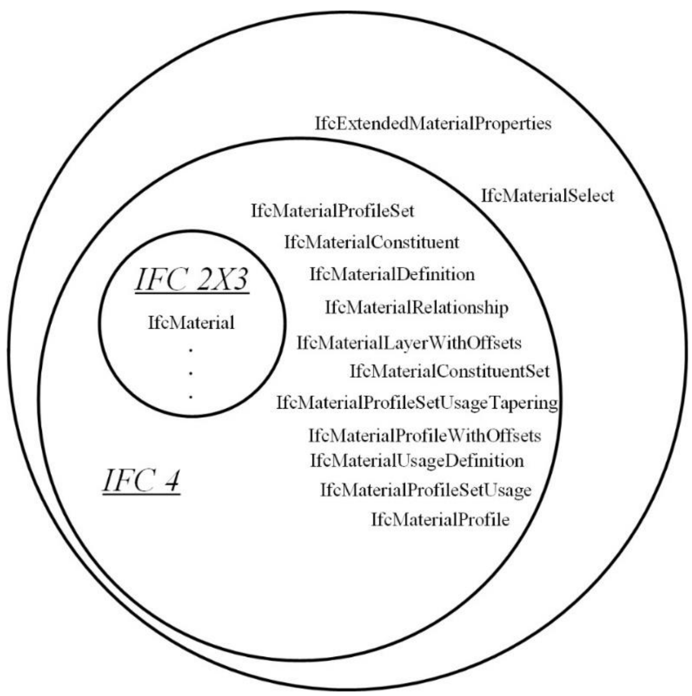


Figure 16. Examples of comparisons of information representation between IFC2X3 and IFC4 MVD versions.

IFC Implementation Version Discussion. In this dissertation, the author adopted the IFC2X3 instead of the IFC4 format model to implement the proposed invariant signature-based information processing method (i.e., information representation and information checking). Although IFC4 is a more recent version of the buildingSMART model data and it is a more advanced version of IFC2X3, IFC2X3 is still dominating in the industry, widely used and accepted in various applications in the AEC domain (buildingSMART 2021; Ren and Zhang 2021a). Previously, IFC2X3 is only based on the Coordination View 2.0 MVD, which aims to use IFC as a reference model to support exchange for the coordination of BIMs during the design phase (BuildingSMART 2021). In contrast, the IFC4 version of MVD supports mvdXML, which is a machine-readable format and makes the checking tool suitable for multiple MVDs. In addition, IFC4 overcomes some limitations of IFC2X3 in terms of MVD improvements (i.e., IFC entity representation, and attribute coverage). In this dissertation, the author chose material information as an example type of information in the IFC model to demonstrate the differences between IFC2X3 and IFC4 versions of MVDs. In terms of model representation, only one attribute "name" is contained in the "IfcMaterialProperties" entity in the IFC2X3 version of MVD. In contrast, there are five attributes "Name", "Description", "Material", "Properties", and "HasExternalReferencesProperties" in the IFC4 version of MVD. In addition, in the IFC4 version, "IfcPropertySingleValue" and "IfcMaterialProperties" entities can be related with the "Property" attribute. But there is no relationship between these two entities in the IFC2X3 version. With respect to information coverage, some entities, such as "IfcMaterialProfileSet", "IfcMaterialConstituent", "IfcMaterialDefinition", and "IfcMaterialRelationship", could be defined in the IFC4 version, but not in the IFC2X3 version.

4.1.2 An MVD and Invariant Signature-Based Information Checking Method

Proposed Information Checking Method

The proposed BIM information checking method includes three main steps (Figure 17): Step (1) - Convert BIMs to IFC format. In this step, different types of BIM data are converted into IFC format. The IFC file will be used as the source of data. Step (2) - Apply information checking algorithm. In this step, the IFC data are checked by our developed information checking algorithm, corresponding to the application context of the IFC data. For example, structural analysis context requires material information and cross-sectional information of the structural components, among others. Architectural model requires material information, color and texture information, among others. Material information is required in many different application contexts. Different types of materials will have different parameter requirements. For example, wood material requires viscoelasticity information whereas steel material requires thermal expansion coefficient. Such required information will be used in the information checking algorithm developed in this method. In parallel to information checking using our algorithm, the IFC data will also be checked manually and using an MVD, respectively. Step (3) – Validate information checking results. In this step, the model information checking results from Step (2) will be validated in two ways: firstly, cross-compare the results between our information checking algorithm, the manual approach, and the MVD-based checking; secondly, conduct structural analysis on the IFC model and validate the information checking results through analyzing the structural analysis results.

Information checking is an important preprocessing step to prepare BIM data for use in analytical BIM applications. This proposed model information checking method supports such preprocessing of BIM. In addition, it indirectly supports the extraction of information from IFC (by verifying if the information exists in the first place) and therefore the mapping and transformation of IFC data into other types of data used in different application scenarios.

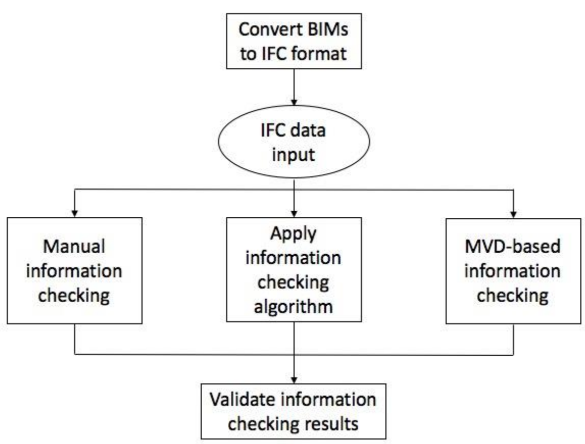


Figure 17. Proposed model information checking method.

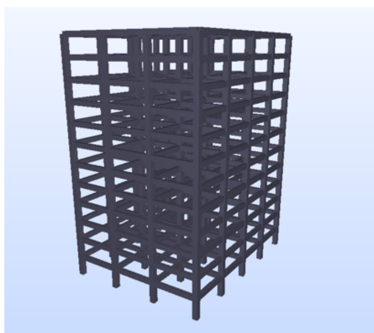
Proposed Information Checking Algorithm Development

The author proposed a framework of material information checking based on augmenting the above MVD models with customized algorithms, based on the proposed invariant material signatures. Among the three main types of materials discussed in this dissertation, the only difference in their MVD validation results would be in the number of entities, because the detailed material information is contained in the “Name” and “NominalValue” attributes of the “IfcPropertySingleValue” entity. E.g., for steel material, seven required entities are checked that contained seven parameters: MassDensity, PoissonRatio, ShearModulus, ThermalExpansionCoefficient, UltimateStress, YieldStress, and YoungsModulus. For concrete material, six required entities are checked for six corresponding parameters: MassDensity, PoissonRatio, ShearModulus, ThermalExpansionCoefficient, CompressiveStrength, and YoungsModulus. Therefore the author picked one (i.e., concrete material) as an example. As part of the material information checking framework, the author developed an IFC-based material information checking algorithm, with a special focus on checking “IfcExtendedMaterialProperties,” “IfcMaterialSelect” entities and detailed parameters of steel, concrete, and wood materials in the AEC domain. Figure 18 shows the flow diagram of this customized material information checking algorithm for augmenting MVD-based checking. The algorithm runs three main steps as follows: (1) Check augmented IFC entity instances (i.e., “IfcExtendedMaterialProperties,” and “IfcMaterialSelect”) based on MVD constraints; (2) Extract material types based on “IfcMaterial” entity instance; and (3) Check specific material parameters from “IfcPropertySingleValue” entity instances based on different material types. This algorithm will terminate after all the material parameters are checked. The results regarding what specific entity information and material parameter information exists or does not exist, will be printed out in a report. Through the developed material information checking algorithm, the missing material information could be identified and used to inform the IFC model developer and user.

Figure 18. Material information checking algorithm augmenting MVD.

4.1.3 Experimental Test for the Proposed Information Representation and Checking Method

The author chose a 12-story concrete model (Figure 19) as the case study model to test the material information representation and checking method. There were three types of material information entities in the IFC model, “IfcMaterial,” “IfcExtendedMaterialProperties,” and “IfcPropertySingleValue.” The results (Figure 20) showed how the six detailed material parameters of the concrete material in our invariant material signatures were represented, where the highlighted content showed such material parameter representation details.



Material Signature

- Mass Density
- Thermal Expansion Coefficient
- Shear Modulus
- Poisson’s Ratio
- Compressive Strength
- Young’s Modulus

IFC 2X3 Concrete

Figure 19. The 12-story concrete building used in case study.

```
#80=IFCEXTENDEDMATERIALPROPERTIES(#86,(#87,#88,#89,#90,#91,#92),$,'STD-CONCRETE');
#86=IFCMATERIAL('STD-CONCRETE');
#87=IFCPROPERTYSINGLEVALUE('CompressiveStrength',$,IFCPRESSUREMEASURE(4.0000000E+003),#26);
#88=IFCPROPERTYSINGLEVALUE('MassDensity',$,IFCMASSDENSITYMEASURE(2.2481827E-004),#23);
#89=IFCPROPERTYSINGLEVALUE('PoissonRatio',$,IFCRATIOMEASURE(1.7000000E-001),$);
#90=IFCPROPERTYSINGLEVALUE('ShearModulus',$,IFCSHEARMODULUSMEASURE(1.3461538E+006),#30);
#91=IFCPROPERTYSINGLEVALUE('ThermalExpansionCoefficient',$,IFCTHERMALEXPANSIONCOEFFICIENTMEASURE(5.5000000E-006),#33);
#92=IFCPROPERTYSINGLEVALUE('YoungModulus',$,IFCMODULUSOFELASTICITYMEASURE(3.1500000E+006),#31);
```

Figure 20. Material information representation implementations in IFC file.

Depending on the software in use, manual information transfer may cover all required information, but it is time consuming and error-prone. Model size is another factor that will affect the information transfer results and a larger model size could significantly increase the manual information transfer time. To evaluate the proposed method in facilitating information transfer between architectural design and structural analysis, the author compared the proposed method with manual information transfer from the time efficiency perspective. A manually developed gold standard was used as the ground truth in the evaluation, which included the material information input for structure analysis from an architectural model. The proposed invariant material signatures were implemented in IFC2X3 representations based on IFC model that was exported from BIM application software, to transfer material information and their parameters to the corresponding material signature. In this case, the model was exported as IFC2X3 version to follow industry practice. Although IFC4 is a more advanced version comparing to IFC2X3 as discussed in Step 5, IFC 2X3 still dominates practical use in the industry, due to its massive market penetration and applications that follow it. The Coordination View 2.0 of IFC2X3 is split into two MVDs in IFC4: (1) the Reference View, which is mainly for viewing and coordination purposes, and referencing domain models to each other; and (2) the Design Transfer View, which is for exchanging IFC models to be used for further design and evaluation tasks. In practice, the Design Transfer View for IFC4 is not fully available, and Coordination View 2.0 for IFC2x3 cannot be fully replaced by the Reference View of IFC4 per se (Liebich 2013). To address that, the author proposed the material signature in which IFC2X3 and IFC4 versions of BIMs could be converged. Table 9 shows the IFC-based invariant material signatures as the destination representations of the conversion process. The first and last columns in the Table 9 represent "Name" and "NominalValue" attributes for each parameter in IFC data, which are related to material definitions. It was not necessary to define every attribute in the entity based on the IFC schema when the model was created. But the "Name" and "NominalValue" attributes must be defined in the IFC file of a model (i.e., an instantiated physical file).

Table 9. IFC-Based Invariant Material Signatures Representation Implementations.

Parameters Name	Unit Information	Material Type	IFC Representations of “NominalValue”
Mass Density	kg/m3	Steel, Concrete, Wood	IfcMassDensityMeasure
Young’s Modulus	N/m2	Steel, Concrete, Wood	IfcModulusOfElasticityMeasure
Shear Modulus	N/m2	Steel, Concrete, Wood	IfcShearModulusMeasure
Poisson’s Ratio		Steel, Concrete, Wood	IfcPositiveRatioMeasure or IfcRatioMeasure
Thermal Expansion Coefficient	°C-1	Steel, Concrete	IfcThermalExpansionCoefficientMeasure
Ultimate Stress, Yield Stress, Compressive Strength	N/m2	Steel, Concrete	IfcPressureMeasure

The author compared the time consumption of the proposed method with that of a manual information transfer. In the manual information transfer the interface of Solibri Model Viewer and Autodesk Revit 2018 were used. The author imported the test case model in the software and clicked through each element to add their material information in the property panel. The manual information transfer took 11 minutes to finish. The time could be further increased significantly with model size and complexity, because the engineers need to click through each element to identify and assign the detailed material parameters to them, then document the material information for further analysis. In comparison, the proposed method enables automated and efficient conversion and transfer of the material information between architectural models and structural models, based on invariant material signature representations using IFC. In the IFC format, the model could use “Name” attribute of “IfcMaterial” entity instance to represent/store material types (e.g., steel, concrete, and wood), and use “Name” and “NominalValue” of “IfcPropertySingleValue” entity instance to represent/store material parameters (e.g., mass density and Young’s modulus). Using the proposed method, all the material information (i.e., material type and its parameters) could be successfully represented, processed, and analyzed (e.g., structural analysis). Table 10 shows the performance comparison of these two methods.

Table 10. Performance Comparison of the Proposed Method with Manual Transfer.

Method	Time Consumption
Manual Transfer	11 mins
Proposed Method	2 mins

Figure 21 shows the IFC model validation/checking results using the MVD augmenting algorithm. The author implemented the algorithm using IfcOpenShell library, which is an open-source library for accessing and processing IFC data. The results showed that the six detailed material parameters of the concrete material were successfully checked by the MVD augmenting algorithm. The highlighted content showed that “IfcMaterialSelect” entity was not found, whereas “IfcExtendedMaterialProperty” and six material parameters were successfully found and extracted in the IFC model. The total time consumption of running augmented algorithm was 48 seconds in a computer with core i5 dual core processer and 8 GB RAM, which could be further reduced with a more powerful machine. In contrast, manual information checking process took 4.2 minutes even after leveraging the search function in the text editor. Table 11 shows the performance comparison of these two methods.

```
[Data] #80=IfcExtendedMaterialProperties(#86,(#87,#88,#89,#90,#91,#92),$,'STD-CONCRETE')
[Info] IfcMaterialSelect doesn't exist
[Data] #86=IfcMaterial('STD-CONCRETE')
[Info] CompressiveStrength exists
[Info] MassDensity exists
[Info] PoissonRatio exists
[Info] ShearModulus exists
[Info] ThermalExpansionCoefficient exists
[Info] YoungModulus exists
[Data] #87=IfcPropertySingleValue('CompressiveStrength',$,IfcPressureMeasure(4.0000000E+003),#26)
[Info] CompressiveStrength
[Info] ['4.0000000E+003']
[Info] PSI
[Data] #88=IfcPropertySingleValue('MassDensity',$,IfcMassDensityMeasure(2.2481827E-004),#23)
[Info] MassDensity
[Info] ['2.2481827E-004']
[Info] ( KILOGRAM ^ 1 ) * ( MILLIMETRE ^ -3 )
[Data] #89=IfcPropertySingleValue('PoissonRatio',$,IfcRatioMeasure(1.7000000E-001),$)
[Info] PoissonRatio
[Info] ['1.7000000E-001']
[Info] None
[Data] #90=IfcPropertySingleValue('ShearModulus',$,IfcShearModulusMeasure(1.3461538E+006),#30)
[Info] ShearModulus
[Info] ['1.3461538E+006']
[Info] ( MILLIMETRE ^ -2 ) * ( NEWTON ^ 1 )
[Data] #91=IfcPropertySingleValue('ThermalExpansionCoefficient',$,IfcThermalExpansionCoefficientMeasure(5.5000000E-006),#33)
[Info] ThermalExpansionCoefficient
[Info] ['5.5000000E-006']
[Info] KELVIN ^ -1
[Data] #92=IfcPropertySingleValue('YoungModulus',$,IfcModulusOfElasticityMeasure(3.1500000E+006),#31)
[Info] YoungModulus
[Info] ['3.1500000E+006']
[Info] ( MILLIMETRE ^ -2 ) * ( NEWTON ^ 1 )
```

Figure 21. Report of material information checking results by customized algorithm.

Table 11. Performance Comparison of the Proposed Information Checking Method with Manual Checking Method.

Method	Time Consumption
Manual Checking	4.2 mins
Proposed Method	0.8 mins

4.2 Information Processing for Construction Monitoring Application

4.2.1 Semantic Rule-Based Construction Procedural Information Extraction Method

Problem Definition

To bridge the gap of integrative automated construction monitoring based on textual information from construction procedural documents, the author proposed a semantic rule-based information extraction method to automatically extract construction execution steps from construction procedural documents, which could be used later in a unified construction procedural data integration (CPDI) framework to integrate planned procedure from construction procedural documents and executed procedure from sensing data that is collected from the construction jobsite. In order to check the sequence of construction execution steps on the construction jobsite, the extracted information from procedural documents is used to guide the selection of sensing techniques to collect corresponding data on the jobsite, then the extracted information from procedural documents and detection results from sensing data can be matched to fulfill the progress monitoring and checking purposes. The proposed IE method is supported by a newly developed construction procedure and data collection (CPDC) ontology, which provides a novel way for construction site information classification and a new instrument to leverage different sensing techniques based on procedural document IE results. The proposed IE method was quantitatively evaluated on construction specification documents to extract execution steps. In addition, sensing technique selection based on the extracted information was qualitatively evaluated.

The proposed semantic rule-based IE method for construction procedural documents includes seven main steps (Figure 22). Step 1: Information Representation - This step defines the content and format of extracted information in the construction procedural documents. Step 2 - Data Preprocessing - This step preprocesses the input procedural documents with tokenization, sentence splitting, morphological analysis techniques, customized symbol removal, and sequence-based text segmentation methods, which prepare the raw textual data for further processing in locating the required information that will be extracted from the documents. Step 3: Feature Engineering - This step generates syntactic and semantic features that represent textual data to help locate semantic information element instances that need to be extracted. Step 4: Semantic Information Elements Identification – This step analyzes the textual data manually to identify the semantic information element instances that will be extracted and their extraction sequence. Step 5: Information Extraction Rules Development – This step develops a set of IE rules to automatically extract and process construction execution steps from procedural documents. Step 6: Information Extraction Rule Application – This step extracts the target information from procedural documents using the developed IE rules in Step 5. Step 7: Evaluation – This step evaluates the extracted information with a manually developed gold standard. The evaluation is iteratively conducted to improve the performance until a satisfactory performance or predefined threshold is achieved.

A semantic rule-based information extraction algorithm for extracting construction execution steps from procedural documents will be developed following these seven steps (Figure 22) for use in a further proposed CPDI framework. The technical details of each step are shown as follows.

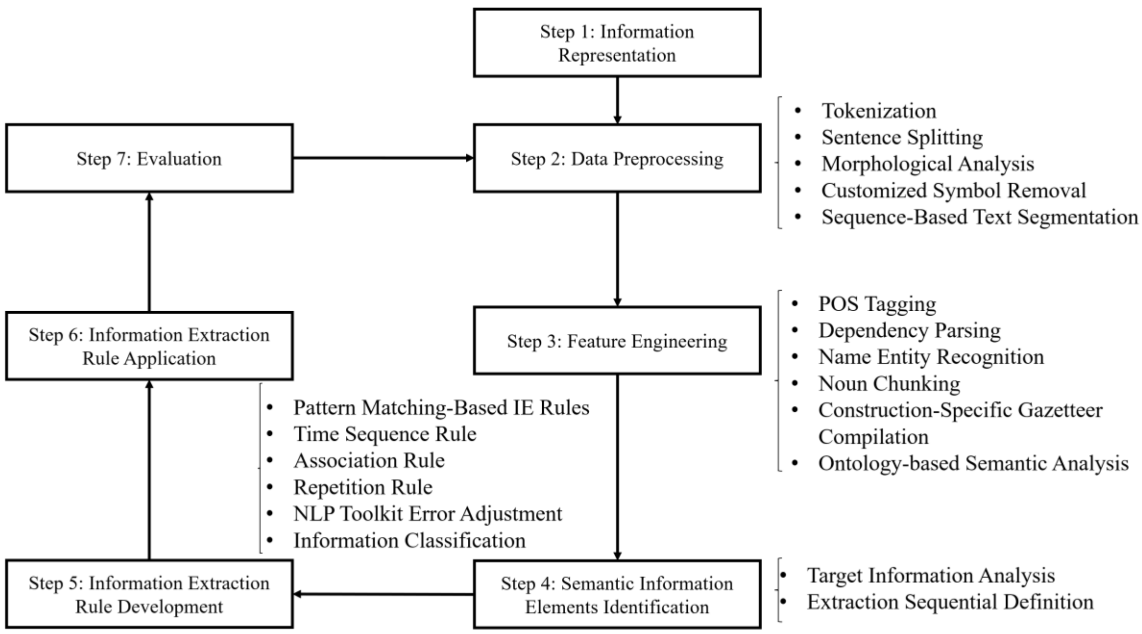


Figure 22. Proposed information extraction method from construction procedural documents.

Step 1: Information Representation

In this method, the execution steps that will be extracted mainly focus on activity (i.e., action, and object), and support information (e.g., time, location, and designated personnel), in which the activity is the focus, the time and location are the essential support information, whereas the rest of the contents, such as qualitative descriptions, are the secondary support information. The representation focuses on activity and support information that can be directly used to guide selection of sensing techniques to collect site data for monitoring. The high-level representation follows: “action + object(s)” or “action + object(s) + support information”, in which: (1) the “action + object(s)” is the necessary information, (2) essential support information (i.e., time and location) provide the main supplementary conditions of the necessary information to check the execution operation, and (3) secondary support information (e.g., personnel, and regulation) is extracted and stored for potential future use. For example, in the sentence “Mix materials thoroughly in a barrel for 3 minutes using a low-speed mixer", "mix materials" is one such activity where "mix" is the "action" and "materials" is the object, "3 minutes" and "in a barrel" are the time and location information (i.e., essential support information) for the "mix materials" activity, respectively. Meanwhile, "using a low speed mixer" is the secondary support information to describe/define the "mix materials" activity. In addition, the rest of the contents except for activity and essential support information, such as regulations, and personnel information (e.g., architect) in the construction procedural documents, are extracted as secondary support information, in which some of them will not be directly used for compliance checking with sensing data (e.g., execution step information) but can be reserved for potential future use (e.g., quality inspection). The support information can be a word (e.g., an adjective and an adverb), a phrase, or a clause that explains the details of an activity. For example, from the sentence: "Prepare surfaces using the methods recommended by the manufacturer for achieving the best result for the substrate under the project conditions," "using the methods recommended by the manufacturer for achieving the best result for the substrate under the project conditions" is extracted as support information of the "prepare surfaces" activity.

Step 2: Data Preprocessing

In this step, three NLP techniques (i.e., tokenization, sentence splitting, and morphological analysis), and two customized preprocessing methods (i.e., symbol removal and sequence-based text segmentation) are adopted to prepare input textual data from Step 1. They help tokenize the input document, split sentences, get root format of a token, remove unnecessary symbols, and segment sentences, respectively. English tokenization is the process to split the English raw text into tokens, such as a word, a number, a punctuation, and a space (Manning and Schutze 1999). This process mainly identifies the unit element of the raw data to parse the text with its boundary. Sentence splitting aims to split the sentences of the text by typical sentence boundaries, such as periods, and question marks. It is similar to tokenization but performs at a sentence level. This process can split a large segment of raw text into sentences to get it ready for further processing. Morphological analysis refers to recognizing the different forms of a word (e.g., plural form of a noun, past tense of a verb) and mapping them to the lexical form of the word (e.g., singular form of a noun, infinitive form of a verb) in a dictionary (Fautsch and Savoy 2009). For example, "installs", "installed", and "installing" are all mapped to "install" when using morphological analysis. In this step, morphological analysis is used to identify concepts (i.e., action) and relations (i.e., objects associated with an action) based on a construction ontology. For example, "installs", and "installed" will both be extracted because "install" is an action concept in the ontology. Morphological analysis simplifies the matching process when implementing compliance checking between sensing data and extracted textual data. Customized symbol removal method is applied before applying the main language processing pipeline. The construction procedural documents are preprocessed by removing non-contributing symbols at certain locations of the contents (e.g., asterisks, blank spaces). Text segmentation is the process of dividing a long text into meaningful units (e.g., words, sentences, or topics), which reflects the subtopic structure of the text. Therefore, the author developed a customized sequence-based text segmentation method in the preprocess pipeline. For example, the text "Clean surfaces thoroughly prior to installation." is segmented into "'Clean surfaces thoroughly', 'prior to installation.'" based on time sequence terms (i.e., prior to) to segment sentence into two sub-activities.

Step 3: Feature Engineering

This step uses a construction ontology to define semantic features, which benefits IE processes beyond using syntactic features only, because the ontology encodes domain specific knowledge. The combination of using syntactic features and semantic features reduces the number of needed patterns during IE rule development. In this step, both syntactic features [e.g., Part-of-Speech (POS) tags, dependency parsing) and semantic features (i.e., concepts from ontology and gazetteer lists) are generated. Accordingly, these features are used to further define the target patterns for extraction.

POS Tagging. POS tagging assigns a tag to each word in a sentence based on its syntactic category (e.g., noun, and verb) (Moens 2006). For example, the tags of "NN" and "JJ" are for singular noun and adjective word in a sentence, respectively. In this step, POS tagging is used to help generate syntactic features. The author aims to extract operation action, associated object(s), and their support information from construction procedural documents. POS tagging provides important syntactic features to extract such information using NLP. For instance, a verb may be describing an action, such as "install," "prepare," and a noun may be describing an object, such as "concrete," "door," etc. All the other processing techniques in this method are built upon and leverage POS tagging, such as noun chunks, dependency parsing, which will be discussed in detail as follows.

Dependency Parsing. Dependency parsing is the task of automatically analyzing the dependency structure of a sentence in a document. Some dependency parsing methods are based on formal grammar that define permissible dependency structures, others are based on inductive machine learning from a large set of sentences with syntactic annotations (Kübler et al. 2009). In this method, dependency parsing and regular expression are used to identify prepositional phrases (e.g., if and where clauses) by extracting the sub-clauses led by prepositions. The prepositional phrases are extracted based on the POS tags that were generated in the previous step. After assigning POS tag to each word in a sentence, a dependency parser can be adopted to analyze how words are connected, resulting in "head" and "child" relationship between words. They are extracted and classified as support information for an activity in the same sentence. For instance, the sentence "Install window in window well with proper tools," "in window well" and "with proper tools" are two prepositional phrases (with prepositions "in" and "with" as heads, "window well" and "proper tools" as children, respectively) that describe the details (i.e., location and method) of the activity "Install window", and those would be extracted by using the preposition head words based on POS tags and categorized as support information.

Name Entity Recognition. Name entity recognition is a technology to classify mentions of entities in unstructured textual data into pre-defined categories (Fan et al. 2020). Name entity recognition serves as an important tool for information extraction and retrieval. An entity is likely to have multiple expressions and it is not only necessary but also important to recognize and categorize those different expressions as one entity in IE. Those entities are often consisted of words with random syntactic tags, such as numbers, noun, verb, and it is better to identify them as a whole by performing named entity recognition. For example, New York, the city of New York, and N.Y., are different expressions of the same location entity. In this method, time and date, laws and regulations in the procedural documents are recognized and extracted as support information using named entity recognition, which are pre-defined categories in a document to be recognized.

Noun Chunks. Noun chunks select a noun plus the words describing the noun. Noun chunks are phrases that have a noun as their head and the words describing it as children nodes in the dependency tree. The head word serves as a semantic head node of the dependency tree and is not necessarily in front of the words describing the head word. For example, it can be used to select specific noun phrases (e.g., fire-rated-door) for describing objects in the documents. By using noun chunking technique in addition to POS tagging, the author can avoid counting the same object multiple times, and can extract meaningful objects. For instance, “door opening” should be one object instead of two objects “door” and “opening”, in addition, “fire rated door” should be extracted as a whole instead of separately as “fire” and “door”.

Construction-Specific Gazetteer. A gazetteer provides a list of words that share the same category (e.g., a list of tools). In this step, a number of words that represent a similar meaning are collected as a gazetteer list. Accordingly, four gazetteer lists are manually developed: (1) a non-operational action gazetteer list to classify non-operational activity actions for sensing technique selection and future integration into the automated framework, such as “notify,” and “contact” etc. These words are not actual operational actions and may not be reflected in sensing data on construction sites. These actions may be detectable through other means such as communications of office clerk (e.g., email and voice); (2) a gazetteer list of non-physical objects on sensed construction site, such as “instruction”; (3) an operational action gazetteer list to recognize operational activity actions, such as “installation,” “cleaning,” “preparation”; and (4) a time sequence phrase gazetteer list of terms to define the order of activities, such as “before,” “when,” and “after,” etc. These key words are used to recognize sentence components’ sequence before extracting execution steps. The operational sequence is an essential piece of information needed for progress monitoring. For instance, in this sentence “Clean the floor after painting walls,” the author pre-processes the sentence by identifying the two activities and their sequence according to the sequence term “after” from the developed gazetteer list. The activities after pre-processing are: “painting walls,” and “clean the floor”.

Ontology-Based Semantic Analysis. In this step, a construction procedure and data collection (CPDC) ontology is developed to recognize the semantic features of the execution steps in the construction procedural documents, which classifies construction site information based on the nature of the activities in the construction documents and whether they could be detected through construction site sensors. In addition, it provides guidance on selecting sensing techniques for collecting jobsite information, which provides a new instrument to jobsite information acquisition. In this method, ideally all the information that appears in the construction procedural document will be considered and compared with sensing data, but there may be non-detectable information by the sensing techniques, such as regulations. The CPDC ontology aims to categorize information on construction jobsite and use them to guide selection of sensing techniques to support decision makings on data collection for designated operations.

As shown in Figure 23 (partial), two areas are covered in the ontology: construction information and sensing technique. In the construction information part, information of construction site is classified into two broad categories: internal information (e.g., labor, equipment, and material) that could be controlled by site personnel, and external information (e.g., meteorological information) that could not be controlled by site personnel. Internal information of construction site is further classified into three sub-categories based on information provided in the construction procedural documents, which are action, object, and support information, respectively. For "action" and "object" subclasses in the ontology, each of them is classified into two categories based on whether it can be detected or measured using available sensing techniques. Action is classified into physical operations (e.g., install and clean) and non-physical actions (e.g., notify and leave), and object is classified into physical objects (e.g., door and frame) and non-physical objects (e.g., document). For "support information" subclass, it is classified into two categories: (1) essential support information (i.e., time and location); and (2) secondary support information (i.e., quantitative information, qualitative information, personnel, and regulation). In the sensing technique part, the author lists possible sensing techniques that can be used in the field based on the types of operations on the jobsite, grounded on literature. Figure 23 shows partially the CPDC ontology, which can classify jobsite information and help users select appropriate sensing techniques for collecting execution data on jobsites.

The proposed method mainly focuses on extracting and classifying information that can be detected by sensing techniques for construction execution sequence checking, other types of information that do not directly contribute to the sequence checking (e.g., regulation) are extracted and classified as support information for future use. In addition, certain execution steps, such as "Verify the adequacy of the contractor's application for payment", are not suitable for processing by jobsite sensing information. While they might be processable with other types of technologies or systems, the processing of those information is out of the scope of this dissertation.

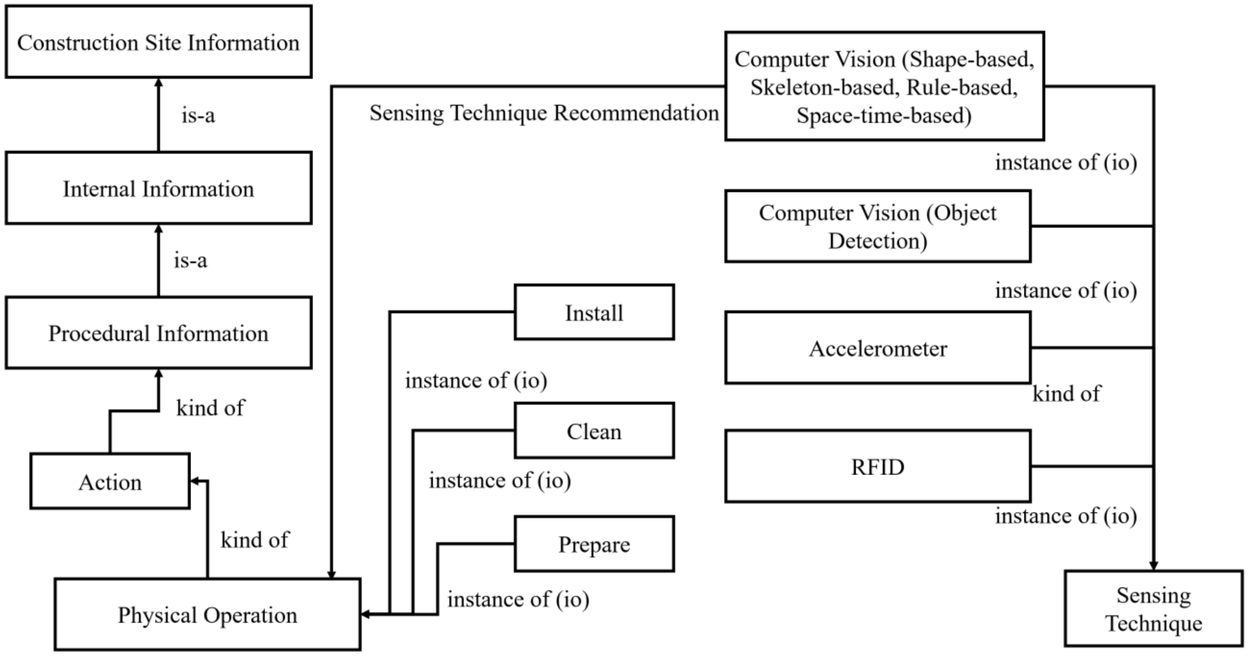


Figure 23. Framework of the developed construction procedure and data collection (CPDC) ontology (partial).

After preprocessing the text, the syntactic and semantic features are selected for further IE rule development. To integrate the planned procedure of a construction procedural document and the executed procedure information from a sensed construction job site, all the execution steps of the internal information in the ontology, including action, object, support information (i.e., time, location, quantitative, qualitative, personnel, and regulation information), are extracted based on the customized semantic IE rules. POS tags, construction gazetteers, dependency parsing, named entity recognition, pattern matching, and noun chunks are selected as main syntactic features. Concepts from the ontology (i.e., action and object) as discussed above and time sequence phrases (e.g., before, and after) from gazetteer lists, are used as semantic features. Semantic features are used to extract domain-specific semantic information, which would be difficult to extract using solely syntactic features.

Step 4: Semantic Information Elements Identification

In this step, construction procedural documents are manually analyzed to identify the types of semantic information elements to be extracted and their sequence of extraction. The extracted semantic information elements include action, object, and support information in a sequence from the documents. In addition, they may or may not include associated objects and their support information of actions based on the type of information provided in the documents.

Target Information Analysis. Before developing the extraction rules in Step 5, the target information should be selected according to the specific requirements of the application. Three essential types of target semantic information for representing execution steps are extracted (i.e., action, object, and support information). The information corresponds to the concepts in the ontology (Figure 23) and components of execution steps. For example, a “door” (a concept in the ontology) belongs to a “physical object” entity (a super-concept in the ontology), which will be extracted as an object of an execution step.

Extraction Sequential Definition. Because a sentence is usually composed of multiple concepts and relations, the sentence is analyzed by extracting primary information (i.e., activities) and support information (e.g., time, location) following a sequential order. It is not efficient if all instances are extracted at the same time, because the amount of possible patterns increase nonlinearly when the number of semantic information increase. In this step, the proposed IE algorithm is used to extract execution steps of construction procedural documents in a sequential manner. After analyzing the dependencies among the target information elements, the order of extraction was the following: action, object, and support information. Actions take the priority in the extraction sequence. The objects are associated with the corresponding actions, which could be extracted right after the actions. Support information is extracted lastly, in which time and location are essential support information that will be extracted before other types of support information (i.e., secondary support information). Object and support information may or may not be extracted based on the extraction order, because if the sentence does not contain action, the rest of the information cannot be extracted either. In this step, because the different activities are already reorganized based on sequence-based text segmentation in Step 2, time sequence phrases do not need to be used.

Step 5: Information Extraction Rules Development

In this step, a set of rules are developed to automatically execute the information extraction process, in which there are two types of rules: (1) pattern matching based core IE rules, and (2) customized supplement IE rules. Core IE rules are developed to automatically extract the instances of target semantic information elements. In addition, to order the activities, eliminate irrelevant and redundant information in IE, three customized supplement IE rules (i.e., time sequence rule, association rule, and repetition rule) are developed to support core IE rules. Then classes of the extracted semantic information element instances are developed based on the components of execution steps (e.g., action, object) and if it is detectable using various sensing techniques, which is beneficial for future information selection and integration into the automated framework.

Pattern Matching-Based IE Rules. Pattern matching aims to check a given sequence of tokens for the presence of the constituents of some patterns. Pattern matching is a method to generate specific terms in the text based on tags of each word in a sentence for information selection. The core IE rules utilize above-mentioned semantic (e.g., ontology concepts) and syntactic features (e.g., POS tags) in Step 3 for pattern composition, all potentially related information pieces are selected as candidate execution steps to help identify potential matching patterns. Patterns are defined in terms of sequences of features to be matched within a requirement. For example, pattern matching can be used to select passive voice of verb phrases or adverb-verb phrases. It is not uncommon to see those verb phrases in a procedural document, such as "is installed," "carefully lift," etc. To preserve the complete action information in extraction results, the author adopts pattern matching technique to extract such action information based on both syntactic and semantic features. For instance, rule-based pattern matching is adopted to extract verb phrases in various forms, such as "ADV+VERB" (e.g., carefully install), "AUX+VERB" (e.g., is installed), "AUX+ADV+VERB" (e.g., is carefully installed), etc. For another example, in text "Install components to manufacturer's written instructions.", a pattern is developed to identify "Install" (using "VERB" POS feature-based pattern matching), "components" (using noun chunking) and "to manufacturer's written instructions" (using dependency tree parsing) as candidate action, object and support information for an execution step, respectively. This flexible configuration ensures the completeness and accuracy of execution step extraction from those different types of expressions due to the inherent complexity of natural language.

Customized Supplement IE Rules (Time Sequence Rule). Time sequence rule aims to re-order execution step activities in one sentence based on time sequence terms (gazetteer list) before applying core IE rules. Time sequence terms (e.g., before, after) are used to classify the order between two execution step activities. As shown in Figure 24, the author summarized common time sequence terms of each construction sequence, which are frequently used in the construction procedural documents. Although there are many situations that describe the order of two execution step activities (e.g., meet, equal, and during) (Huang et al. 2019), in this dissertation, the sequence is classified in two main types: successive relationship, and parallel relationship. Three or more execution step activities can be decomposed into multiple pairs of two execution step activities based on the structure of the procedural document. For instance, in the execution step "Install flooring after properly cleaning substrates," there are two activities, "install flooring" and "cleaning substrates," connected by time sequence term "after". In this case, the execution step is divided into two short sentences and arranged according to the time sequence word, i.e., "After properly cleaning substrates" and "Install flooring," before extracting execution step (i.e., action, object and their support information). This process makes sure the extracted information is in a correct order.

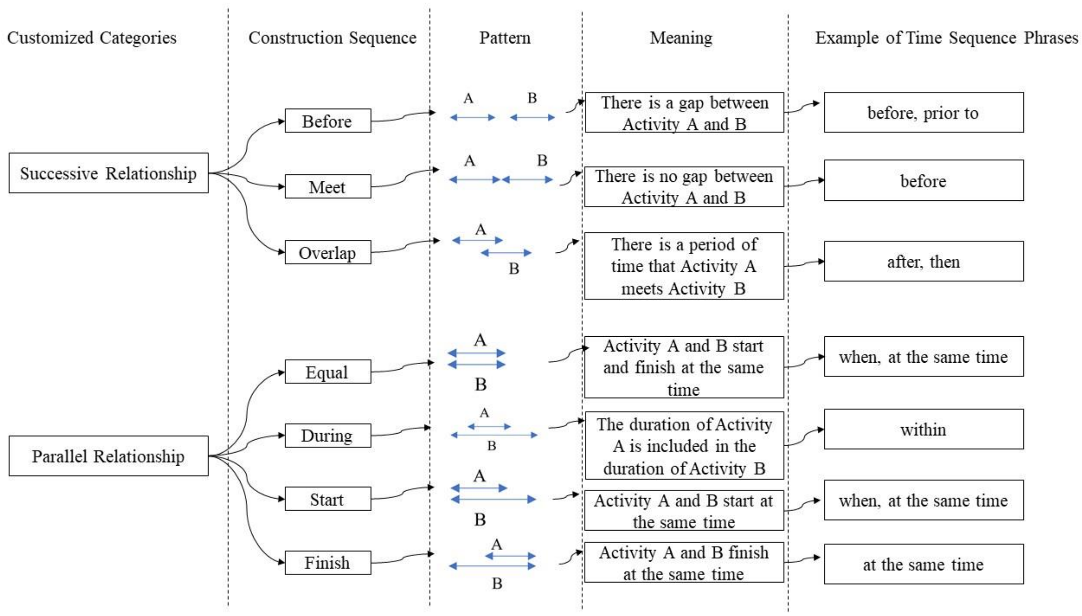


Figure 24. Classifications and demonstration of order sequence of two execution step activities.

Customized Supplement IE Rules (Association Rule). Association rule is developed to define candidate information that will be extracted using core IE rules. In the proposed IE method, the execution steps are represented as "action + object(s) + support information" phrases from each sentence in the procedural documents. Accordingly, when developing the association rule, only the selected information consisted of action verbs (or gerunds) with/without object nouns and their support information from the sentences are extracted. If there is no action in a sentence to be extracted, the object and support information will not be extracted either, because actions are the essential information of the execution steps, which demonstrates the execution operation in a construction project. Sometimes, objects may not directly follow associated action. For example, for "prior to installation" in the context of the procedural documents, associated object of the "installation" is the object in the section title. In our method, the author extracts the dangling verb "installation" solely in the beginning sentence of the documents, and automatically assign associated object that is from section title.

Customized Supplement IE Rules (Repetition Rule). A repetition rule is implemented to preserve only one instance of the same activity (i.e., action-object pair) per execution step in a sentence to eliminate potential repetition. Based on repetition rule, only one execution step activity is extracted when there are two or more occurrences of the same term in one sentence. For instance, in the following sentence "Install window frame to manufacture's written instruction, the alignment, squareness, twist and plumbness of installed window frame are to be no more than 1/16 inches", "install window frame" occurred twice in one execution step (extracted verbs are converted to original form through morphological analysis, i.e., "installed" is also extracted as "install") but semantically there is only one installation action. Other unrelated information that neither belongs to the activity information nor the essential support information will be eliminated during the following step.

NLP Toolkit Error Adjustment. To remove unnecessary information in the execution steps (i.e., information that is extracted based on defined patterns using NLP toolkit and categorized into execution steps, but does not belong to either actions, objects, or essential support information of the execution steps), error adjustment is automatically performed after IE. For example, the phrase "in accordance with" will be extracted as a noun phrase after dependency parsing and categorized as an object. In reality, it is not an object in the activity of execution steps, because it only means that an activity should be in compliance with some specific standards. In this case, because this type of information cannot be filtered using NLP toolkit, an NLP Toolkit Error Adjustment algorithm is developed to automatically eliminate such information from execution steps accordingly.

Information Classification. In this step, all the processed information is written into a CSV file, in which each column represents an information category (e.g., action, object, time, location). In addition, each category of information is assigned a Boolean value to represent if it is sensing technique detectable or non-sensing technique detectable. The physical operations, physical objects, some support information (e.g., quantitative information, location, personnel) are sensing technique detectable information. The non-physical actions, non-physical objects, and other support information (e.g., regulations) are also extracted and classified as non-sensing technique detectable information. For example, in the IE procedure, in the sentence of “Install components to manufacturer's written instructions,” “to manufacturer's written instructions” is extracted as non-sensing technique detectable support information of the “install components” activity.

Step 6: Information Extraction Rule Application

This step aims to extract the target information elements from the construction procedural documents using the developed core IE rules and customized supplement IE rules in Step 5. For example, after implementing time sequence rule and association rule, the text “Do not begin installation until substrates have been properly prepared.” is processed into two activities “‘prepared substrates’, and ‘begin installation door and frame’” with the sequence as listed.

Step 7: Evaluation

The proposed IE method is evaluated using precision, recall, and F1-measure of generated execution steps [Eq. (1) to (3)] (Goutte and Gaussier 2005). A manually developed gold standard is used as ground truth in the evaluation, which includes the generation of construction execution steps in the procedural documents. Figure 25 demonstrates an example of the gold standard, the gold standard is developed by manually extracting and classifying textual data of a construction procedural document. Generally, at least three researchers (i.e., annotators) develop the gold standard by identifying all semantic information element instances from each sentence. For execution steps labeling, the annotators compare two versions - initial annotations (versions A and B) and the annotations after several steps of discussion and adjustment (version FINAL). The quality of the gold standard is evaluated by Fleiss’ kappa factor of inter-annotator agreement based on Eq. (4) to (8), in which n is the number of annotators, N is the number of labelled specifications, k demonstrates labelled situations/results, n_ij represents the number of annotators who assigned the i-th specification to the j-th annotated results/situation, P_i computes how many annotator-

annotator pairs are in agreement for each specification, p_j calculates the proportion of labelled documents in the j-th annotated result/situation to all labelled documents (Falotico and Quatto 2015), and adjusted if needed. Fleiss' kappa is a statistical measure of the initial inter-annotator agreement for assessing the reliability of agreement among a fixed number of annotators when labelling items. It is adopted to measure how well multiple annotators can make the annotation decision for a certain category in a gold standard (Artstein 2017).

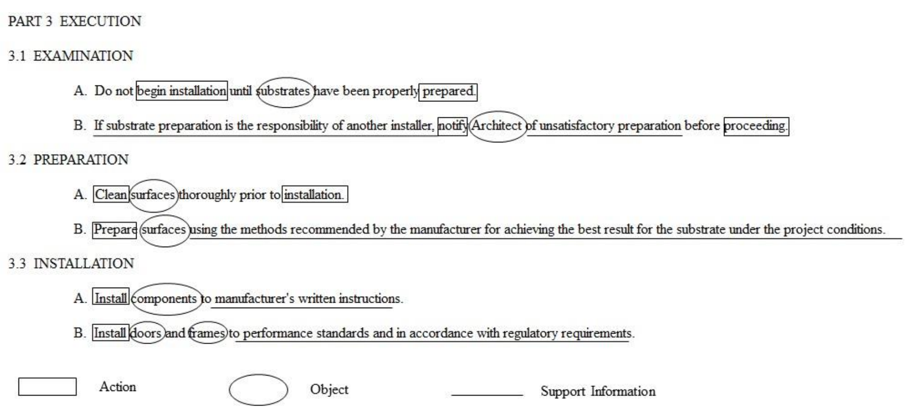


Figure 25. An example piece of a gold standard from construction specifications.

$$Precision = \frac{True\ Positives}{True\ Positives + False\ Positives} \quad (1)$$

$$Recall = \frac{True\ Positives}{True\ Positives + False\ Negatives} \quad (2)$$

$$F1 = 2 * \frac{Precision * Recall}{Precision + Recall} \quad (3)$$

$$p_j = \frac{1}{Nn} \sum_{i=1}^{N} n_{ij} \quad (4)$$

$$P_i = \frac{1}{n(n-1)} \sum_{j=1}^{k} n_{ij}(n_{ij} - 1) \quad (5)$$

$$\bar{P} = \frac{1}{N} \sum_{i=1}^{N} P_i \quad (6)$$

$$\overline{P_e} = \sum_{j=1}^{k} p_j^2 \qquad (7)$$

$$k = \frac{\bar{P} - \overline{P_e}}{1 - \overline{P_e}} \qquad (8)$$

4.2.2 Experimental Implementation and Result Analyses for the Proposed IE Method

Experiment Implementation

The open-source library spaCy (spaCy 2015) for advanced NLP in Python (Oliphant 2007) was used to develop the text processing pipeline and implement the following NLP techniques to implement the pattern matching-based core IE rules: English tokenization, rule-based morphology analysis, parts-of-speech tagging, dependency parsing, named entity recognition, and noun chunking. Meanwhile, three customized supplement IE rules (e.g., time sequence rule) were integrated into Python programming language to perform the IE procedure (Python 3.5.3). The CPDC ontology was developed based on nature of the objects in the construction documents and whether they could be detected in construction sensing data. It helps select semantic information elements (i.e., execution steps) and classify information into a comma-separated values (CSV) file for future information selection and integration for the automated framework (e.g., action, object, time, location), and guide sensing technique selection for construction jobsite data collection.

The CSI specification was selected to help develop and test the IE algorithm, because CSI is a national association of more than 8,000 construction industry professionals who are experts in building construction and the materials used therein. Specifications include detailed descriptions of construction work processes dedicated to a specific construction project. Based on the definition in the Dictionary of Architecture and Construction, a specification is, "a written document describing in detail the scope of work, materials to be used, methods of installation, and quality of workmanship for a parcel of work to be placed under contract; usually utilized in conjunction with working (contract) drawings in building construction" (Harris 2006). Execution steps from the construction specification play an important role in communicating construction procedure of specific tasks of a project to the job site personnel.

The selected specifications are separated into two sets: training set for helping IE algorithm development, and testing set for algorithm evaluation, which contain 35 and 11 specifications, respectively. The information extraction algorithm was developed based on training set, i.e., execution procedure with SECTION 08 (e.g., 08 11 10, 08 11 16, and 08 15 00) of the CSI Master Formatted Specifications for Openings (Dunbarton 2020; Cline Doors 2020; PGT 2020; AMBICO 2020; Sweets 2020).

Experimental Test

An experiment was conducted on a set of open-source specifications of the testing set to evaluate the IE algorithm. It was checked for execution procedure with SECTION 08 of the CSI 3-Part Formatted Specifications for Openings (ARCAT 2020). In the experiment, the author inputs project execution section of the specification to be processed, which provided construction execution steps in each sub-procedure of a construction project. Figure 26 shown a partial example of the input specification in the experiment.

PART 3 EXECUTION

3.1 EXAMINATION

A. Do not begin installation until substrates have been properly prepared.

B. If substrate preparation is the responsibility of another installer, notify Architect of unsatisfactory preparation before proceeding.

3.2 PREPARATION

A. Clean surfaces thoroughly prior to installation.

B. Prepare surfaces using the methods recommended by the manufacturer for achieving the best result for the substrate under the project conditions.

3.3 INSTALLATION

A. Install components to manufacturer's written instructions.

B. Install doors and frames to performance standards and in accordance with regulatory requirements.

C. Coordinate with wall construction for anchor placement.

Figure 26. Example of the original contents of execution section of construction specifications.

As illustrated in Figure 27, the input specification in Figure 26 was preprocessed (Step 2) into intermediate files by removing spaces and other symbols at the beginning of the document, splitting sentences using sentence splitters, segmenting each sentence into sub-activities based on time sequence phrases, and reorganizing activities based on the order information obtained from time sequence phrases, respectively.

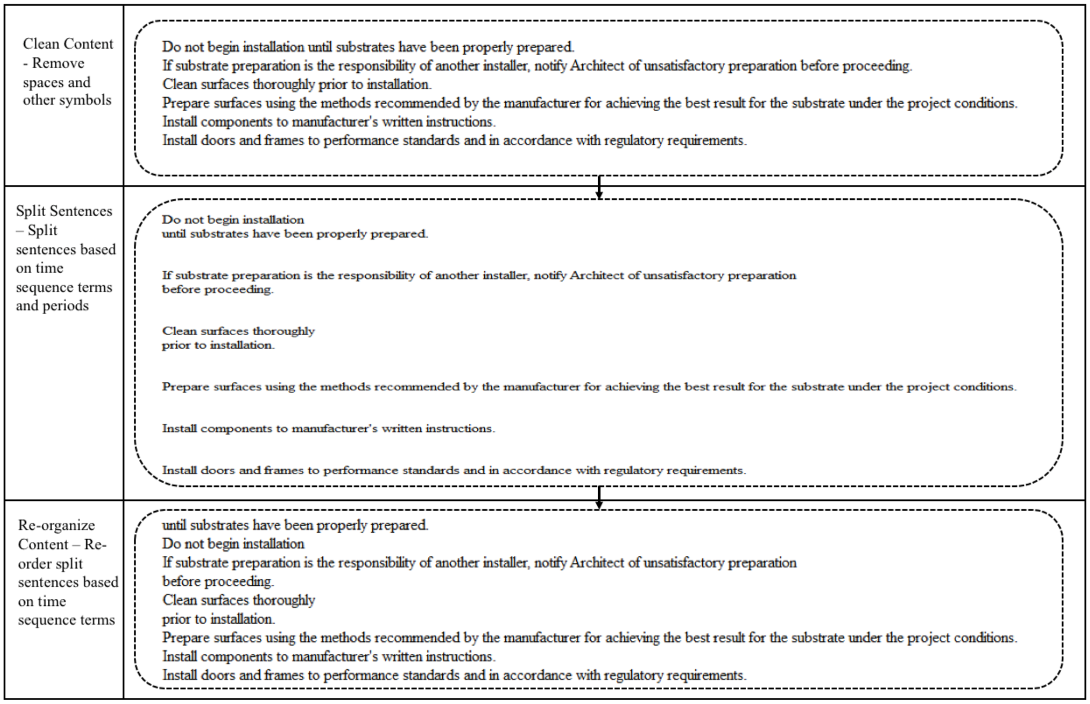


Figure 27. Intermediate files of specification preprocessing results.

After implementing IE rules, the required information was extracted and stored in different columns in a CSV file (e.g., action, object, time, location). In order to eliminate the variation of syntactic forms of words for easy integration to the proposed automated framework, only lemmatized forms are stored in the CSV file. For instance, “prepares,” “prepared,” “preparing” are mapped to “prepare” and stored in the CSV file. In addition, they were categorized as sensing technique detectable or non-sensing technique detectable information (with their Boolean values). The category of sensing technique detectable information provided data that would be checked with sensing data as execution steps for future applications (e.g., progress monitoring and checking). However, certain information (e.g., OSHA regulations) relies on human observation and measurement to compare rather than detecting using sensing techniques, the author extracted such information and saved as support information for future examination or reference. For instance, this information can be compared with inspection reports or measurement results. Figure 28 showed an illustrative example of extracted semantic information element instances in the specification.

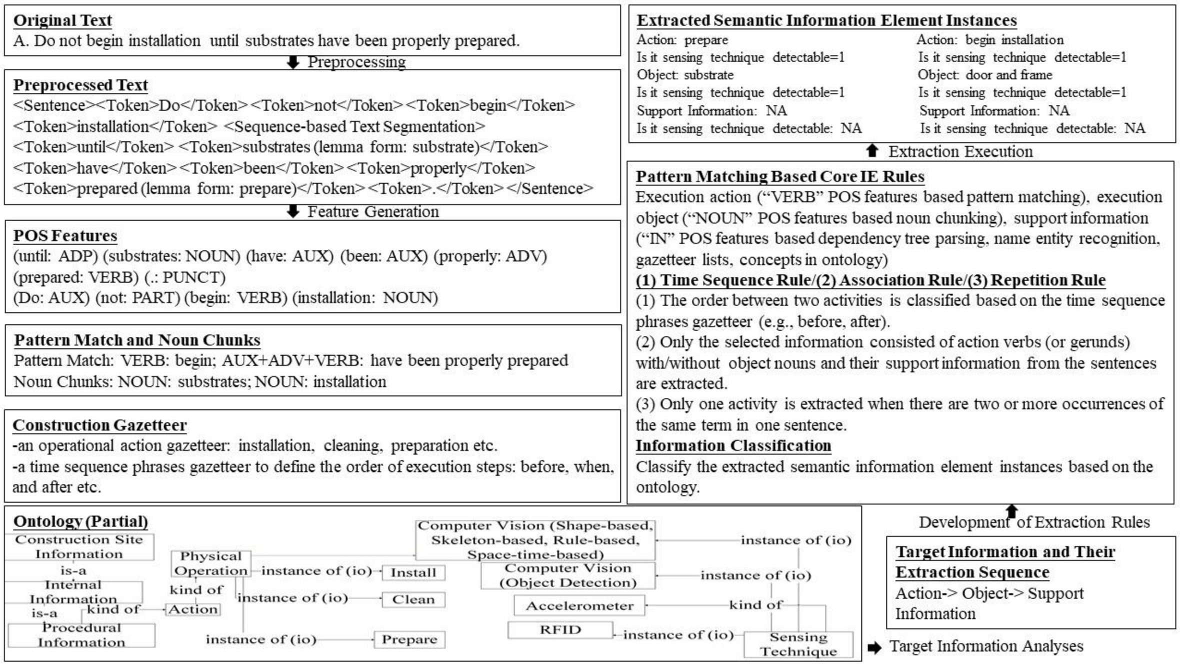


Figure 28. An illustrative example of the extracted information from the textual data.

Evaluation

Fleiss' kappa statistical measure was adopted to evaluate inter-annotator agreement of manually developed gold standard by three independent annotators, it checked the reliability of agreement among them. Table 12 demonstrated the parameters that were used for calculating evaluation result k of inter-annotator agreement. In this method, three annotators (i.e., n in Eq. (4) to (6)) developed gold standard based on eleven specifications (i.e., N in Eq. (4) to (6)) in the experiment. Firstly, three annotators independently labelled each specification (version A in Step 7: Evaluation). Secondly, three annotators conducted self-checking on version A, and provided version B (in Step 7 Evaluation). Thirdly, three annotators discussed several steps and adjusted labels in version B to provide version FINAL (in Step 7 Evaluation). After summarizing the annotation results: (1) 5 instances were incorrectly labelled in a specification; (2) 3 instances were incorrectly labelled in a specification; (3) there was no disagreement for any instances in a specification; (4) 1 instance contained extra label in a specification; (5) 2 instances contained extra labels in a specification. So the number -5, -3, 0, +1, +2 of labelled instances were adjusted to the total labelled semantic information element instances in the final version of the gold standard of each specification (Table 12). For example, the first row in Table 12 shows that three annotators labelled semantic information element instances with the same results for the first specification therefore all the three annotators fell into the column for 0 (i.e., there was no disagreement for any instances in a specification). Based on the provided value of parameters and Eq. (4) to (8), k =0.8370, which demonstrated that the results achieved almost perfect agreement (i.e., 0.81-1.00 indicates almost perfect agreement; 0.61-0.80 indicates substantial agreement; 0.41-0.60 indicates moderate agreement; 0.21-0.40 indicates fair agreement; 0.01-0.20 indicates slight agreement; <0 indicates poor agreement) (Landis and Koch 1977).

Table 12. Inter-Annotator Agreement Results of Gold Standard Comparison of Three Annotators.

Specification n_{ij}	-5: 5 instances were incorrectly labelled	-3: 3 instances were incorrectly labelled	0: there was no disagreement for any instances	+1: 1 instance contained extra label	+2: 2 instances contained extra labels	P_i
1st	0	0	3 annotators	0	0	1
2nd	2 annotators	0	0	1 annotator	0	0.3333
3rd	0	0	0	0	3 annotators	1
4th	0	3 annotators	0	0	0	1
5th	0	0	0	3 annotators	0	1
6th	0	3 annotators	0	0	0	1
7th	0	0	3 annotators	0	0	1
8th	0	0	0	3 annotators	0	1
9th	0	0	3 annotators	0	0	1
10th	0	3 annotators	0	0	0	1
11th	0	0	2 annotators	1 annotator	0	0.3333
Total	2 annotators	9 annotators	11 annotators	8 annotators	3 annotators	
p_j	0.0606	0.2727	0.3333	0.2424	0.0909	

Table 13 demonstrated the evaluation performance of the proposed IE method for execution steps extraction. The number of patterns used to extract “Action,” “Object,” “Support Information” were 259, 187, and 136, respectively. The gold standard includes 268, 191, and 147 instances of “Action,” “Object,” and “Support Information”, respectively. A performance of 97.08% precision and 93.23% recall for execution steps IE were achieved, which indicates that the proposed IE algorithm is effective in extracting execution steps from construction procedural documents. In addition, the extracted support information maintains the completeness of the execution steps in the procedural documents.

Error analysis resulted in three findings. Firstly, the reason for the relatively low precision of “object” and “support information” IE was the use of the customized Association Rule. Because the Association Rule defined that “object” and “support information” are associated with their “action,” which means that if the “action” is not extracted, the associated “object” and/or “support information” cannot be extracted either. In the future, the author will improve the IE rules, such as, adding a morphological rule that will incorporate more gerunds of execution step actions in the construction procedural documents to improve the precision of “action” extraction, accordingly to improve the precision of associated “object” and “support information” extractions. In addition, manually incorporated algorithms can be developed to eliminate the irrelevant object information and support information extractions. Secondly, the reason for the relatively low recall of “support information” was mainly because the limited definitions or usage of defined dependency structures of a clause in a sentence. In the future, the author will incorporate more syntactic structure of a clause in a sentence into NLP techniques to define the clauses when selecting “support information” in the procedural documents. Thirdly, the reasons for the relatively low recall of “object” were the internal errors when using the open-source library spaCy for advanced NLP in Python, as follows: (1) The word “glazing” in execution step activity “install glazing” was extracted as a verb when extracting defined patterns thus it was classified into the “action” category. But in reality, it is a noun that should be selected and extracted into the “object” category based on the meaning in the documents; (2) a noun (i.e., metal) was identified as an adjective, which was not selected or extracted as an “object” of the action of execution steps; and (3) a noun in a clause of support information was identified and extracted as an “object,” which was not an object of an action based on the meaning in the documents. For example, in text “Install door according to instructions,” “instructions” was incorrectly extracted as an object for “install” action.

In the future, the author will improve the use of the construction-specific gazetteer to help select and extract domain specific concepts.

Table 13. Testing Performance of Information Extraction for Execution Steps IE.

Number of Instances	Action	Object	Support Information	Total
In Gold Standard	268	191	147	606
Extracted	259	187	136	582
Correctly Extracted	254	178	133	565
Precision	0.9807	0.9519	0.9779	0.9708
Recall	0.9478	0.9319	0.9048	0.9323
F1	0.9640	0.9418	0.9399	0.9512

4.2.3 Construction Ontology-Based Jobsite Sensing Guidance

IE Results for Sensing Technique Selection. After execution steps were extracted from construction procedural documents, the IE results were used to provide guidance on sensing techniques selection based on CPDC ontology. For example, in the text "A. Do not begin installation until substrates have been properly prepared." (Figure 28), there were two activities extracted using the proposed IE method: "prepare substrate" and "begin installation door and frame," with a sequence as described. There was a dangling verb "installation" that is contained in the first sentence in the document, the object "door and frame" from section title was automatically added as associated object. Because the actions "prepare" and "begin installation" are the concepts from "Physical Operation" entity of CPDC ontology, therefore skeleton-based human activity recognition technique is recommended for collecting activity sensing data on the jobsite (Shi et al. 2019). In addition, the objects "substrate" and "door and frame" are concepts from "Physical Object" entity of CPDC ontology, therefore, machine vision detection technology and object detection are recommended for collecting object sensing data on the jobsite, respectively (Yang et al. 2009, Tian et al. 2010). The IE results are used as the criteria/instruction to guide sensing techniques selection for collecting data on the jobsite based on the developed CPDC ontology, which classifies the construction site information and demonstrates the relationship between construction information and preferred sensing techniques to collect for future information monitoring.

CHAPTER 5 – HETEROGENEOUS DATA PROCESSING AT THE SERVICE AND APPLICATION LEVEL

A portion of this chapter was previously published by:

"Semantic Rule-Based Construction Procedural Information Extraction to Guide Jobsite Sensing and Monitoring." *Journal of Computing in Civil Engineering*, 35(6), 04021026. DOI: 10.1061/(ASCE)CP.1943-5487.0000971.

"A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions." *Advances in Civil Engineering*, 2021.
https://doi.org/10.1155/2021/8824613

"A BIM Information Processing Framework to Facilitate Enriched BIM Applications." *Proc., ASCE Construction Research Congress*, ASCE, Reston, VA, accepted.

"An Integrated Framework to Support Construction Monitoring Automation Using Natural Language Processing and Sensing Technologies." *Proc., 2021 ASCE International Conference on Computing in Civil Engineering*, in press.

"An Ontology-Based Interface to Guide Jobsite Sensing and Construction Tasks/Applications to Support Construction Information Management." In Preparation

5.1 BIM-Based Construction Applications

5.1.1 Information Checking, Provision, and Application Process (ICPAP) Framework

To integrate and leverage different types of information among all the phases of the life cycle of a facility and implement it to support various construction tasks and applications, in this dissertation, an ICPAP framework is proposed to demonstrate an all-in-one-place information management framework, including model information analysis, guided information provision based on user requirements, and information consumption application to support different tasks and functions. The proposed ICPAP framework for enriched BIM applications mainly focuses on four steps (Figure 29). Step 1: Model Information Analysis – This step represents, extracts, and checks the needed information from inputted IFC model. The needed information will be represented in the IFC format, extracted from inputted model, and checked to see if the needed information exists or does not exit, respectively. Step 2: Guided Information Provision – This step provides the recommendations regarding information selections based on user input requirements, such as material selection based on input parameters (e.g., stress, strain, and Young's modulus). The information from Step 1 and Step 2 could be used as the input for Step 3, which provides the reference information that could be implemented in different BIM applications. Step 3: Information Consumption Application – This step implements the extracted information from an IFC model in Step 1 and the recommendations provided in Step 2 to support various BIM applications, such as structural analysis based on geometric information from Step 1 and material information from Step 2, and material cost estimation based on the extracted quantitative information from Step 1 and recommended material types from Step 2. Step 4: Framework Evaluation – This step evaluates the proposed ICPAP framework from time efficiency and accuracy perspectives.

The proposed ICPAP framework consisted of three levels: model level, service level, and implementation level. At the model level, IFC model is used as the input, which contains different types of data for the life cycle of a facility. The output will be the: (1) selected information represented in the IFC format; (2) extracted information based on requirements from the model; and (3) information checking results regarding if the required information exists or not. Information backed in IFC model plays an essential role to support information representation, extraction and checking processes at the model level. At the service level, the input information is the user requirements. For example, the user could select the range requirements of the material parameters (e.g., stress, strain, and Young's modulus), the material type recommendations will be provided correspondingly. A customized dataset is developed based on exploring literature and online resources to help provide recommendations based on user inputs. At the implementation level, the extracted information from Step 1 and the recommendations that are provided from Step 2 could be integrated and implemented into different enriched BIM applications, such as structural analysis, and cost estimation. For example, the quantitative and dimensional information could be extracted from Step 1 that will be integrated with the material selection recommendations from Step 2 to compute the material cost estimation. The dataset that will be used in the different BIM applications is based on referenced literature and online resources (e.g., supplier websites for cost estimation and green building codes for energy efficiency application).

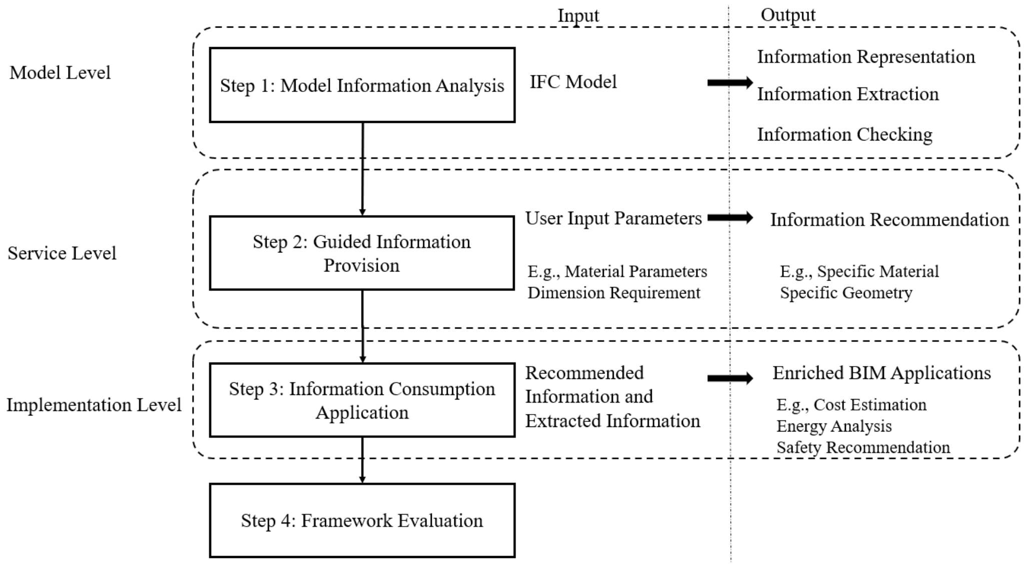


Figure 29. Proposed information checking, provision, and application process (ICPAP) framework.

Step 1: Model Information Analysis

IFC models are developed to cover all needed information in the context of integrating the life cycle information requirements of a facility, including design activities, and construction and maintenance management, among others (Kiviniemi et al. 2005). An IFC model contains both entity information that represents elements of a building (e.g., geometric information and material type) and attribute information that demonstrates functional information of the entity (e.g., material parameters, and dimensional information) (Ren and Zhang 2019). For example, in the content of an entity information in an IFC file, "#80=IFCEXTENDEDMATERIALPROPERTIES (#86, (#87,#88,#89,#90,#91,#92),$,'STD-CONCRETE');" "#80" is the line number, "IFCEXTENDEDMATERIALPROPERTIES" is the entity name, "'STD-CONCRETE'" is an attribute value of the entity to represent the material type. Therefore, an attribute value could be extracted to describe characteristics of an entity in an IFC model. In this step, IFC models are inputted into the ICPAP framework, which then represents needed information in the IFC format, extracts necessary information from the IFC model, and checks its existence to further support information integration and application.

Step 2: Guided Information Provision

Decision making plays an essential role for successes in any domain, especially in the AEC domain that contains a variety of information sourced in different ways. Therefore, making an efficient and accurate decision could contribute to the success of an AEC project. A large portion of construction processes are consisted of different requirements, tasks, and procedures, which contain various factors and conditions that need to be considered (Jato-Espino et al. 2014). Therefore, to fulfill different application requirements, leveraging existing information to make a suitable decision in an efficient manner becomes important for construction project management. This step automatically and efficiently provides information recommendations based on the user requirements and the feasibility of the selection. For instance, general carbon and alloy steel materials will be provided based on the parameter ranges that are inputted from a user (e.g., Material Type: steel material, Mass Density: 7-8 g/cc, Young's Modulus: 300-350 MPa, and Shear Modulus: 70-80 GPa). After inputting requirements (e.g., parameters, and dimensional information), the corresponding recommendations will be provided automatically. The recommended information is based on analyzing referenced literature and other information sources such as matweb.com (MatWeb 2021).

Step 3: Information Consumption Application

Enriched BIM tasks and applications in the construction domain need the support by different types of information, including geometric information, material information, dimensional information, and load information, among others. An IFC model as a data conveyer provides the necessary information that can be extracted and used to support various BIM applications. In this step, the information extracted from Step 1 and the provided recommendations from Step 2 could be integrated, analyzed, and selected to support various construction tasks and applications, such as structural analysis and cost estimation. For example, the dimensional and quantitative information that is extracted from an IFC model in Step 1, and material recommendation that is provided in Step 2 could be used to help conduct material cost estimation. The process of generating construction information to support various BIM applications will be conducted based on automatically exploring and parsing online sources.

Step 4: Framework Evaluation

This step evaluates the proposed ICPAP framework from time efficiency and accuracy perspectives, in which the information representation, extraction, and checking methods in Step 1 will be compared with pure manual information representation, extraction, and checking, respectively. An example of information provision in Step 2 and a proposed BIM application in Step 3 will be presented in the experiment below to demonstrate the adaptability and feasibility of the proposed ICPAP framework.

5.1.2 Experimental Results and Discussion for the Proposed ICPAP Framework

Experimental Implementation

In order to integrate the three functions (i.e., model information analysis, guided information provision, and information consumption application) in the proposed ICPAP framework, a user-friendly interface was developed to implement the proposed framework (Figure 30). For the interface development, Python programming language (Python 3.5.3) was used, in which an open-source IfcOpenShell library was adopted to process IFC data, and three open-source libraries (i.e., tkinter package, SQLite library, and win32api library) were used to help develop graphic user interface for integration into the main processing algorithm. In this dissertation, the author mainly focused on material information to demonstrate the functions of the proposed framework, in which the model information analysis, guided information provision, and information consumption application are discussed around material information.

The ICPAP framework-based interface covers three main functions: model information analysis, guided information provision, and information consumption application. For model information analysis, the user could select an IFC model by clicking on the first button (i.e., "Choose an IFC file"), the corresponding content of the IFC file would be demonstrated in the text display box (white) at the top of the interface. Then the user could select the information representation method in either manual or automatic mode by clicking on corresponding buttons (i.e., "Information Representation_Manual" or "Information Representation_Auto"). In terms of manual information representation, the notepad plus plus software (7.8.8 version) will be opened to demonstrate the IFC file, which will help users read IFC file to represent and extract needed information. When selecting automatic information representation method, the users could choose material properties (e.g., mass density, and shear modulus) in the list box at the center of the interface. For example, “IfcShearModulusMeasure” is the IFC representation of the Shear Modulus parameter of material that is demonstrated in the text display box (dark green). Similarly, users could select information checking method in either manual or automatic mode. The material type and its parameters could be demonstrated and a user report would be generated automatically regarding what material entity information and its parameter information exists or does not exist (Ren and Zhang 2021a). In addition, the BIM Vision software (2.24.4 version) would be opened when users selected automatic information checking method. The material information would be extracted automatically when a user pressed the “Information Extraction” button. For guided information provision, the user could select the range of specific parameters of different material types, then the material recommendations would be provided based on the user input after clicking on the “Please Provide Material Suggestion” button. Consequently, for information consumption application, the cost estimation would be provided based on the material information recommendation from Step 2 and extracted information from Step 1. The provided material information recommendation and the cost estimation information come from the databases that are developed based on manually exploring referenced literature and online resources.

Experimental Test

An experiment was conducted to test the ICPAP framework, in which the 12-storey concrete IFC model (Figure 19) was selected as an input file for testing. In this dissertation, the author mainly focused on material information implementation. In the proposed framework, the material information was represented in the IFC format, extracted, and checked based on concrete material type. The proposed material selection recommendation and cost estimation could be provided based on the range of specific material parameters that the user input, and the extracted information in the IFC model. Figure 31 demonstrates an example use of the proposed framework. In this example, the 12-storey concrete model was imported as the input file into the framework. One specific material parameter (i.e., Shear Modulus) was represented in the IFC format (i.e., IfcShearModulusMeasure), extracted from the IFC model [i.e., #90=IfcPropertySingleValue(‘ShearModulus’,$,IfcShearModulusMeasure(1.3461538E+006),#30)], and checked if it is in the file (i.e., [Info] ShearModulus exists). In addition, plain concrete material would be provided based on the parameter ranges that were inputted from user (i.e., Material Type: concrete material, Young's Modulus: 40-45 GPa, and Shear Modulus: 5-7 MPa) (Li and Li 2010). Then the cost estimation information would be provided based on visiting the supplier website (e.g., Menards.com).

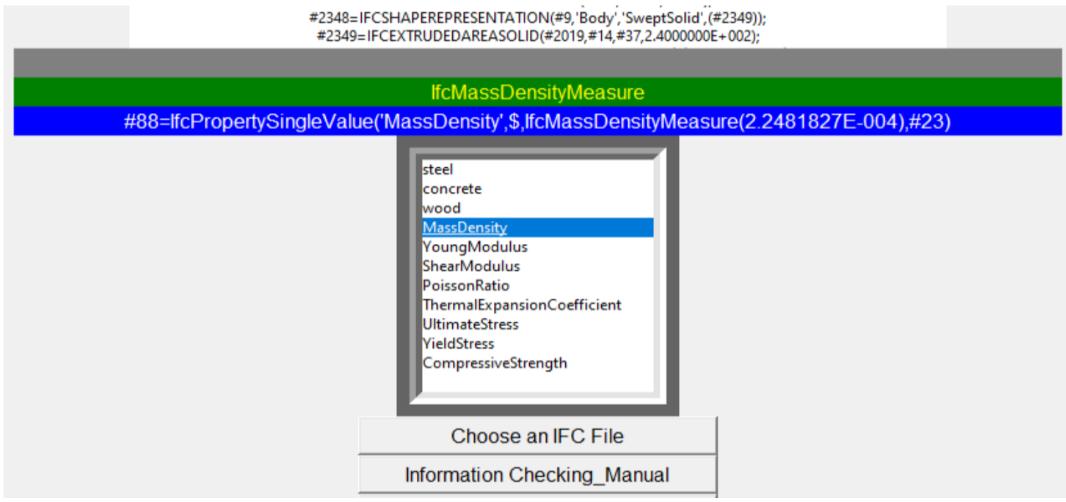


Figure 30. A user-friendly interface to implement the proposed ICPAP framework (partial).

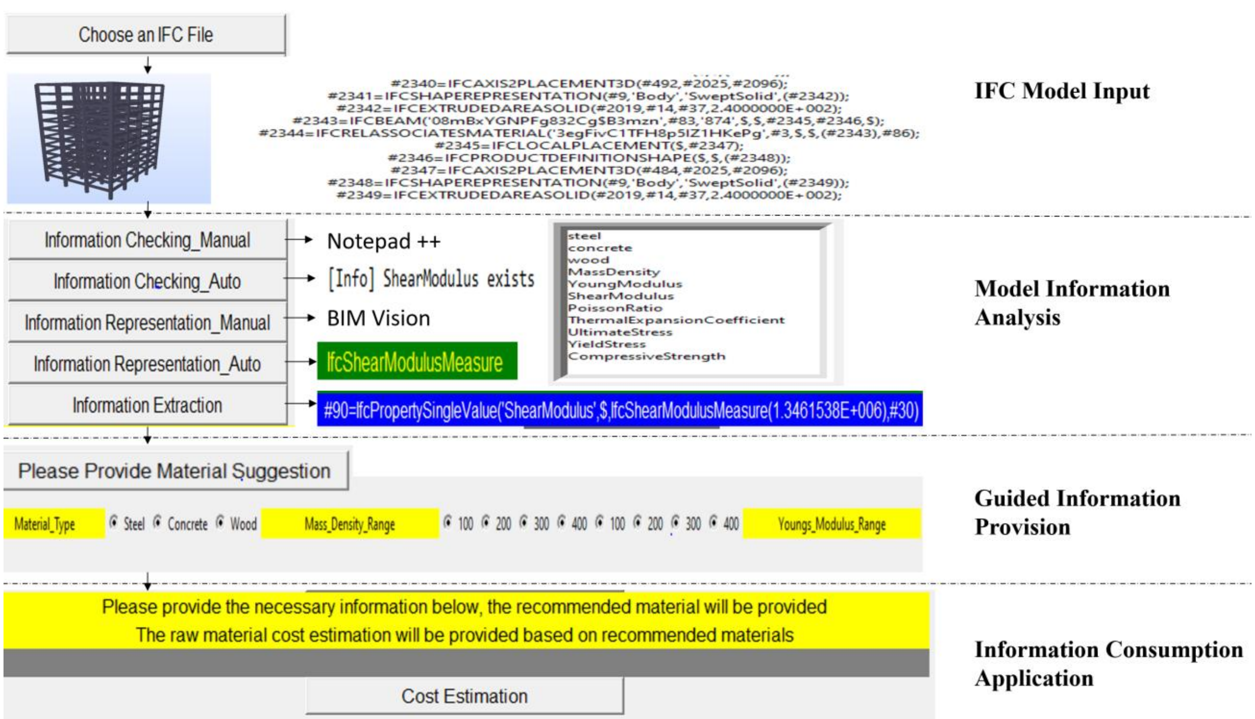


Figure 31. An illustrative example of the use of the proposed framework.

Evaluation

The proposed ICPAP framework was evaluated in terms of time efficiency and accuracy. Table 14 demonstrates the evaluation results. Manual information representation, checking, and extraction took 4.7 minutes, 6.8 minutes, and 6.2 minutes, respectively. Meanwhile, automatic information representation, checking, and extraction took 5 seconds, 2 seconds, and 2 seconds, respectively. In addition, manual information representation method achieved 83.33% accuracy because of human error. Manual information checking and extraction methods both achieved 100 % accuracy after double checking. However, automatic information representation, checking, and extraction methods all achieved 100% accuracy in the first iteration. The evaluation results demonstrate that the ICPAP framework is promising to represent, check, and extract needed information to support information provision and applications. It could be easily adopted to fulfill enriched BIM applications for various tasks in the AEC domain.

Table 14. ICPAP Framework Evaluation Results.

Method	Number of Instances	Time Consumption	Accuracy
Information Representation-Manual	6	4.7 minutes	83.33%
Information Representation-Automatic	6	5 seconds	100 %
Information Checking-Manual	7	6.8 minutes	100 %
Information Checking- Automatic	7	2 seconds	100 %
Information Extraction- Manual	7	6.2 minutes	100 %
Information Extraction- Automatic	7	2 seconds	100 %

5.2 Construction Information-Based Monitoring Application

5.2.1 Construction Monitoring Framework

The author proposed a seven-step integrated construction monitoring framework as follows (Figure 32). Step 1: Construction Procedural Document Input - This step inputs the construction procedural document, in which the planned construction execution steps in each sub-procedure (e.g., opening construction, finishes) of a construction project will be used as the instructions to follow. Step 2: Information Extraction - This step extracts the required information (i.e., execution steps) from the procedural document and exports an eXtensible Markup Language (XML) file. Step 3: Annotation Information Postprocessing - This step postprocesses the XML file from Step 2 by structuring the annotated execution steps in an organized list, to be used in Step 7. Step 4: Sensed Video Input - This step inputs the corresponding surveillance video that is captured from the construction jobsite, which provides the construction execution procedure to be monitored based on the planned execution in the procedural document in Step 1. Step 5: Sensed Video Analysis – This step analyzes the input surveillance video and returns a text file with labels of the activities (e.g., door installation) detected from the input video frames. Step 6: Label Information Postprocessing - This step postprocesses the labels from Step 5 by reducing repetitions in consecutive frames and within the same video frame by considering real-world scenarios. Step 7: Compliance Checking Integration – This step integrates and compares the respectively processed annotation file and label file from Steps 3 & 6, to check the compliance of construction procedure on the jobsite with the planned execution. A user report is generated regarding compliant/noncompliant activities.

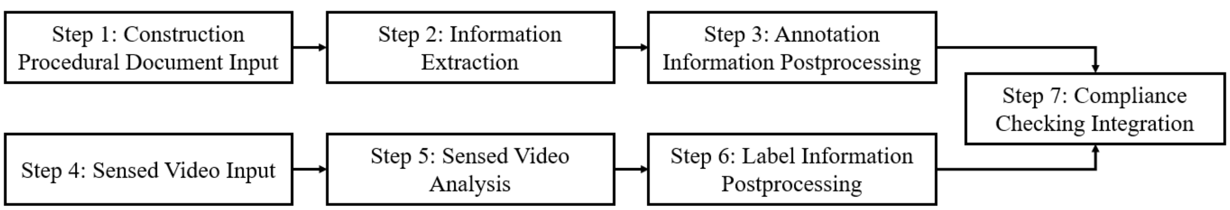


Figure 32. Proposed construction monitoring framework.

5.2.2 Experiment, Results, and Analysis for Construction Monitoring Framework

To test the proposed framework, an experiment was conducted on a test case developed based on the specifications of the AMBICO LIMITED products (ARCAT 2021). The author synthesized related videos with execution steps of the selected specifications, which included installation, cleaning, and excavation preparation activities.

Step 1: Construction Procedural Document Input.

SECTION 08 11 00 of the *CSI 3-Part Formatted Specifications for Openings* was randomly selected as the procedural document input (AMBICO 2020). CSI specifications were used because most of the listing resources of the construction products followed CSI Master Format (CSI 2017).

Step 2: Information Extraction

The author implemented NLP-based IE algorithms and extracted execution steps including actions (i.e., installation, preparation, etc.), associated objects (i.e., wood, door, etc.), negation terms (i.e., not, no, etc.), and time sequence phrases (i.e., before, until, etc.) in each step of execution in the procedural document. The General Architecture for Text Engineering (GATE)'s Processing Resources were used to implement the extraction process (University of Sheffield 2021), including: English Tokenizer, Sentence Splitter, A Nearly-New Information Extraction (ANNIE) Gazetteer which consisted of a collection of lists (e.g., actions and objects). In addition, the author developed Java Annotation Patterns Engine (JAPE) transducer rules which defined regular expression-based grammars to use for extraction. The IE algorithms interfaced with the Processing Resources using GATE's API 7.0 (Zhang and El-Gohary 2017). An XML file with annotations that depict extraction results was exported from GATE (Figure 33) to be used in Step 3. There was no error found in the information extraction step.

PART 3 EXECUTION

3.1 EXAMINATION

A. Do <negative gate:gateId="1193" rule="negative">not</negative> begin <verb gate:gateId="1167" rule="verbextract">installation</verb> <timesequence gate:gateId="1162" rule="sequenceextract">until</timesequence> <object gate:gateId="1196" rule="element">substrates</object> <verb gate:gateId="1168" rule="verbextract">have been</verb> properly <verb gate:gateId="1169" rule="verbextract">prepared</verb>.

B. If <object gate:gateId="1197" rule="element">substrate</object> <verb gate:gateId="1170" rule="verbextract">preparation</verb> is the responsibility of another installer, notify Architect of unsatisfactory <verb gate:gateId="1171" rule="verbextract">preparation</verb> <timesequence gate:gateId="1163" rule="sequenceextract">before</timesequence> <verb gate:gateId="1172" rule="verbextract">proceeding</verb>.

3.2 PREPARATION

A. <verb gate:gateId="1173" rule="verbextract">Clean</verb> <object gate:gateId="1198" rule="element">surfaces</object> thoroughly <timesequence gate:gateId="1164" rule="sequenceextract">prior to</timesequence> <verb gate:gateId="1174" rule="verbextract">installation</verb>.

B. <verb gate:gateId="1175" rule="verbextract">Prepare</verb> <object gate:gateId="1199" rule="element">surfaces</object> using the methods recommended by the manufacturer for achieving the best result for the <object gate:gateId="1200" rule="element">substrate</object> under the project conditions.

Figure 33. An example of the execution steps from construction specifications with corresponding extraction annotations.

Step 3: Annotation Information Postprocessing

In this step, Python programming language (Python 3.5.3) was used to implement the annotation information postprocessing algorithm. The annotations of objects, actions, negation terms, and time sequence phrases were extracted from the exported XML file (Figure 34(a)) and matched to customized Gazetteer lists in GATE to obtain actions and objects of execution steps. In addition, customized time sequence rules were used to re-organize the activities based on different time sequence situations (e.g., before, not … until). The re-organized execution steps were written into an intermediate file (Figure 34(b)) to be integrated and processed in Step 7. For example, the first step of *Section 3.2 PREPARATION* in the specifications was "*Clean surfaces thoroughly prior to installation*". "Clean" action would be kept in this step, and the "installation" action would be checked in the following step to make sure the correct sequence in the specifications was followed. In this method, the algorithm extracted the dangling verb "installation" solely in the beginning sentence of the documents, and automatically assigned associated object that was from section title. Figure 35 illustrated the procedure of postprocessing.

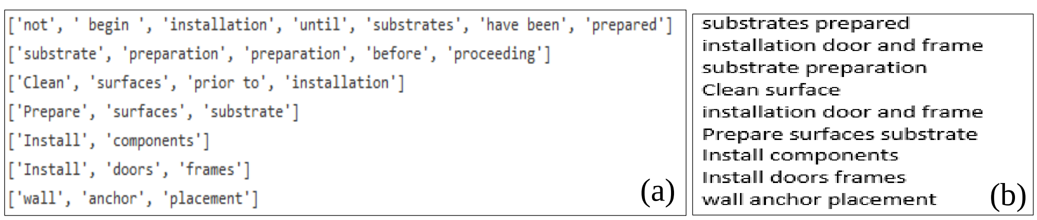


Figure 34. (a): An example of the extracted annotations, (b): An example of postprocessed annotations results.

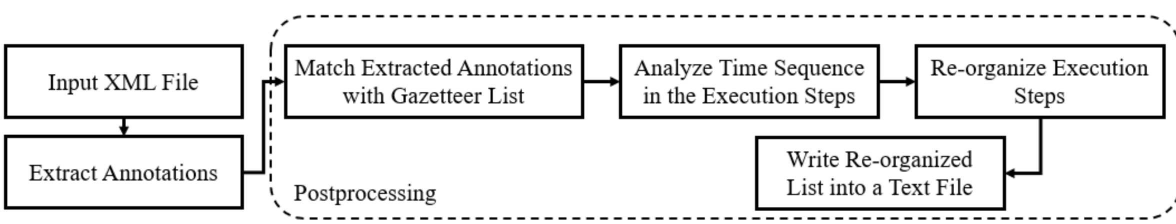


Figure 35. Procedure of annotation information postprocessing.

Step 4: Sensed Video Input

The synthesized video of construction jobsite was inputted into the implementation system of the proposed monitoring framework, to be analyzed in Step 5.

Step 5: Sensed Video Analysis

Efficiency plays an important role when applying the proposed monitoring framework to implement it in a real-world project. To achieve real-time service, you-only-look-once version3 (YOLOv3) was selected as the classifier to detect the activities, which was a state-of-the-art real-time object detection model (Redmon and Farhadi 2018). YOLOv3 split up each video frame image into a grid, in which each region of the grid was predicted by a convolutional neural network (CNN) and the bounding box for each detected class was returned. To evaluate the detection performance, the author created a customized coco-format (a notation format for labels) dataset. The dataset included 6 classes: 3 actions (i.e., installation, preparation, and cleaning) and 3 associated objects (i.e., wood, excavator, and wall). The dataset contained 800 frames that were extracted from 12 videos, four videos for each action, and the associated objects varied for each action (Figure 36). Among the frames, 80% were used for training and validation, and 20% were used for testing. Each frame was labeled independently. In addition, a corresponding .txt file with the same name as the labeled frame was created simultaneously, depicting the labeled class and its bounding box information. The customized configuration file and pre-trained CNN weight file were imported to perform training on the training dataset. For testing, the customized configuration file and trained weight file were added to the model to use. Testing results of the trained model were shown in Table 15 based on the parameters/metrics of total loss (i.e., the value of error function, a smaller total loss indicates a higher prediction accuracy), mean average precision (i.e., average precision across all labeled classes), intersection over union (IoU) norm (i.e., intersection area of predicted bounding box and labeled area over union of the two, IoU = 1 means predicted bounding box coincides with the labeled area), recall (i.e., true positive over the sum of true positive and false negative) and F1-score (harmonic mean of precision and recall) (Redmon and Farhadi 2018). The gold standard included labels for different classes/execution steps in the video. Detection results of each action and object using this trained model are shown in Table 16. The low precision of "wood" object was because the author did not label all the wood pieces when preparing the dataset due to its extensive complexity, so the trained detectors could not detect all the related wood objects in each frame (Figure 36). An example is shown in Figure 37(a) where an installation action with associated wood object were successfully detected.

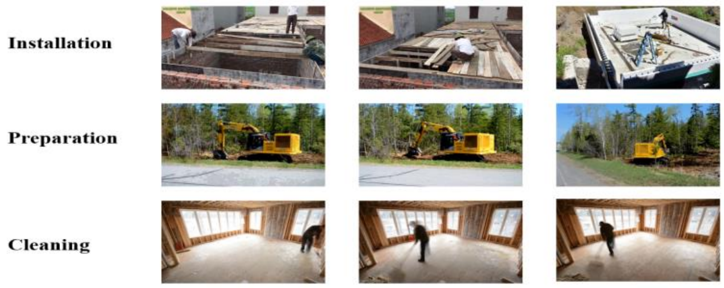


Figure 36. Examples of customized dataset.

Table 15. Testing Performance of Trained Model.

Total Loss	Mean Average Precision	Recall	F1-Score	Intersection over Union (IoU) Norm
0.23	0.88	0.86	0.87	0.75

Table 16. Detection Results of Each Activity and Object.

Class	Preparation	Installation	Cleaning	Wood	Excavator	Wall
Precision	83.23%	81.23%	92.02%	45.47%	93.2%	93.77%

Step 6: Label Information Postprocessing

Label information post processing was implemented in Python. The regular expression (i.e., “re”) module in Python was used to extract the semantic features from the labels based on pattern matching. An example of the postprocessing result and the algorithm flow diagram are shown in Figure 37(b) and Figure 38, respectively.

Figure 37. (a): Successful detection of installation action with associated wood object, (b): An example of post processing labels.

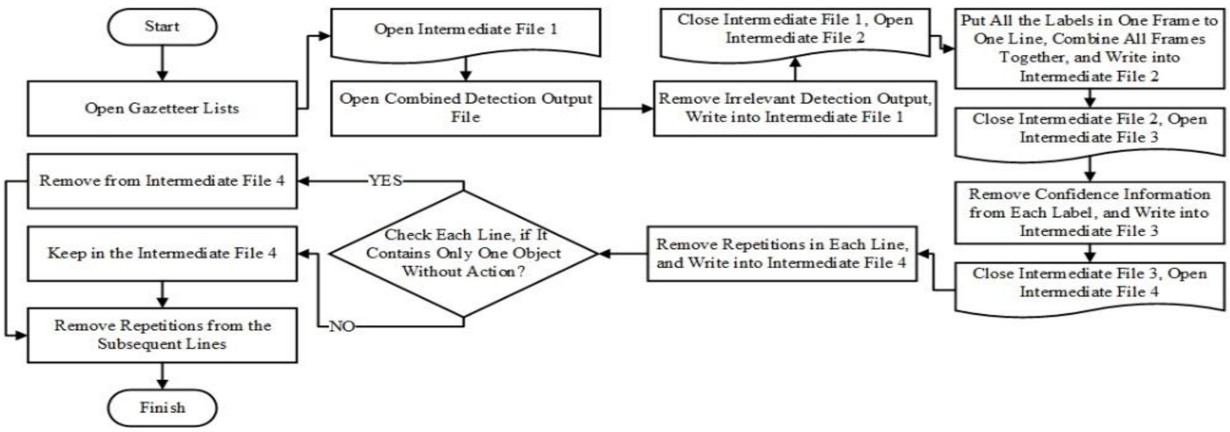


Figure 38. Flowchart of labels postprocessing.

Step 7: Compliance Checking Integration

The information input, extraction, analysis, and postprocessing algorithms for project procedural document and surveillance video could be executed in parallel. After that, longest common subsequence algorithm was implemented in Python to help identify similarity (i.e., longest common subsequence of execution steps) between planned execution steps of procedural document and processed labels of sensed video data (Figure 39). The user report regarding steps that have been executed correctly or incorrectly was then generated (Figure 40).

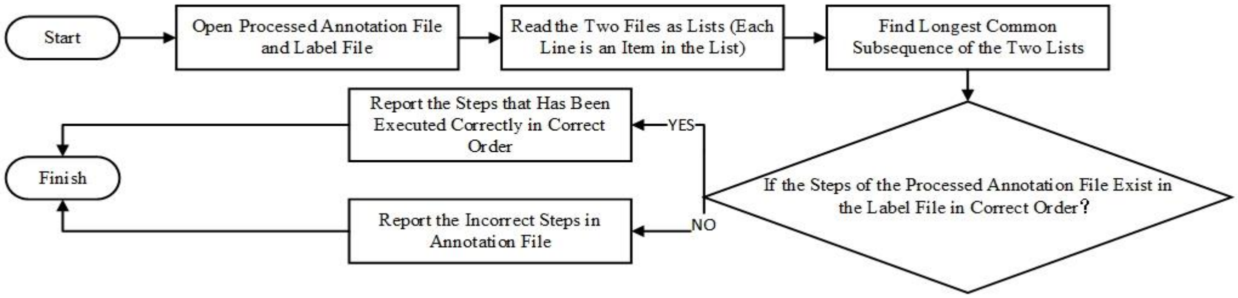


Figure 39. Process of monitoring framework integration.

Figure 40. (a): An example of newly developed label data, (b): Compliance checking of construction execution steps using the label data.

Result Analysis and Discussion

Table 17 shows the evaluation performance of the proposed monitoring framework. In this experiment, the author tested the framework on seven execution steps from the used procedural document (i.e., specifications). Only one execution step ("notify architect of unsatisfactory preparation before proceeding") could not be generated as it was not a video-detectable activity in this discussion. Overall, 83.84% recall and 71.43% precision were obtained for construction execution steps compliance checking. The gold standard was developed by three researchers through manually generating planned execution steps from procedural document, then comparing them with execution procedure in the surveillance video to generate a list of executed steps that would be compared with user report. This shows that the proposed monitoring framework is promising. In execution steps generation, recall is more important than precision (Zhang and El-Gohary 2016). Recall errors are more critical because they could lead to wrong execution steps undetected, whereas precision errors could be eliminated by later double-checking and filtering by the user.

Table 17. Evaluation Performance of the Proposed Monitoring Framework.

Parameter	Number of execution steps in gold standard	Number of execution steps generated	Number of execution steps correctly generated	Precision of execution steps generated	Recall of execution steps generated	F1-measure of execution steps generated
Results	6	**7**	5	71.43%	83.33%	76.92%

5.2.3 IE Method-Based General Implementation Framework of Construction Monitoring Application- Construction Procedural Data Integration (CPDI) Framework

Traditional construction progress monitoring requires a physical site observation, which includes observing/monitoring materials, workers, equipment, etc. on the jobsite based on construction procedural documents. During this process, two types of information are extracted and compared: planned procedure from construction procedural documents, and executed procedure on the construction site that needs to be monitored. To incorporate construction procedural documents into an automated progress monitoring procedure, the author proposed a construction procedural data integration (CPDI) framework, which can integrate operational requirements from construction documents and execution operations from monitored construction jobsite leveraging NLP and sensing techniques (e.g., computer vision, RFID) (Figure 41).

In this framework, the author focuses on monitoring sequence of execution steps on the construction jobsite, which will be checked based on construction procedural documents. The proposed CPDI framework can analyze two types of data simultaneously (Figure 41) as explained below. Procedural Document Input - This step inputs a construction procedural document, in which the construction execution steps will be used as the instruction in the framework. Sensed Construction Site Information Input - This step inputs the corresponding sensing data that is captured from a construction jobsite, which provides the execution procedure that will be monitored based on the construction procedural document. Textual Information Processing – This step analyzes input textual data from the procedural document, and extracts execution steps based on IE rules. Sensing Data Analysis and Label Information Processing – This step analyzes input sensing data from construction job site, and returns a detection result file, in addition, processes the result file for matching and checking under the CPDI framework. Framework Integration – This step integrates and compares the processed IE file and the processed detection result file to check the compliance of job site execution steps with corresponding construction procedural requirements. For instance, the execution step (e.g., install door, on the door frame) was extracted from procedural document using textual information extraction and processing model, in addition, the sensing data processing model will be used to detect the corresponding action (i.e., install), associated object (i.e., door), and their support information (i.e., on the door frame) from the input sensing data and return detection result after post-processing (i.e., install door, door frame), then the integration model will process the extracted information from document and detection results from sensing data to conduct sequence compliance checking and return report to users providing if the correct execution steps exist and in a right sequence based on input documents. The integration model compares clauses of extracted information from textual information extraction and processing model and clauses of detection results from sensing data processing model. The two models extract, analyze, and process data at the same time based on the customized rules to eliminate irrelevant and redundant information and make sure the process sequences both in the textual document and sensing data are comparable.

The ultimate goal of IE in the proposed CPDI framework is to select suitable sensing techniques based on the extracted information from procedural document, collect sensing data from construction jobsite, then integrate the extracted execution steps from construction procedural document with construction execution operations from corresponding sensing data collected, which enables real time automated monitoring of the construction site.

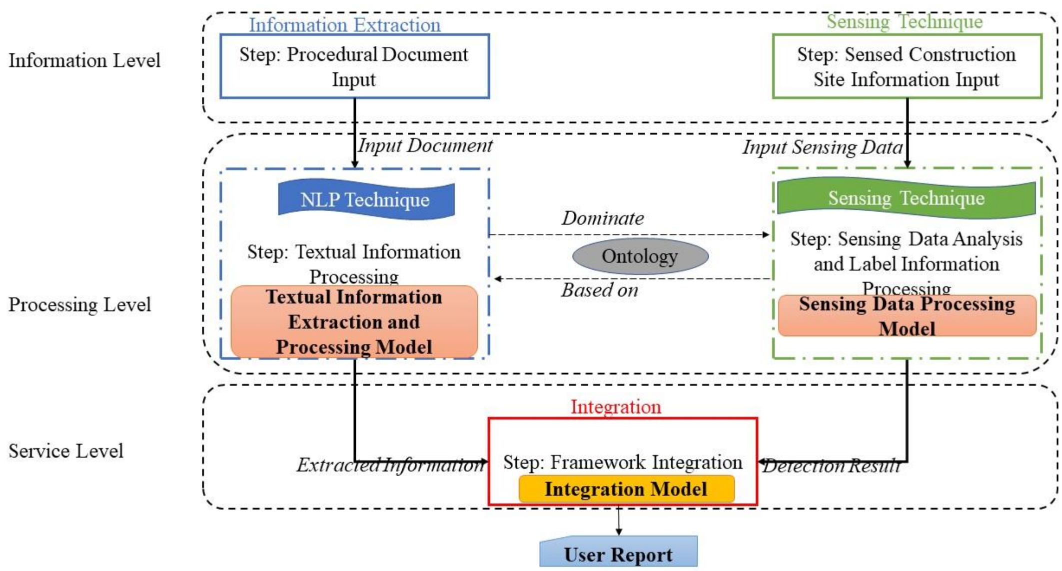


Figure 41. Construction procedural data integration (CPDI) framework.

General Application Extensions of the Proposed IE Method and CPDI Framework

The proposed IE method can be applied to virtually any textual document in the construction domain, such as designer specifications, contractor method statements, which requires only the adjustment in the use of a corresponding ontology. The proposed method serves as a general-purpose IE for execution action, associated object, time, location, and personnel, etc. For example, the IE method can process the contents of a work breakdown structure (WBS) and extract action, object, duration and other support information (e.g., start/finish time).

The proposed IE method and the CPDI framework can be extended to any domain applications that require textual information and activity information that need to be matched/compared. For example, the proposed method and framework can be applied to lab monitoring in educational settings, IE method can extract demo procedure in the documents and monitor students' operations based on the captured sensing data.

5.3 Ontology-Based Construction Jobsite Sensing Technique Guidance and Application

5.3.1 Construction Tasks, Resources, and Techniques Integrated (ConTaRTI) Ontology

Construction information management needs to leverage different types of data represented in different formats, such as planned construction execution information in the construction procedural documents, and equipment information (e.g., location, movement, operational status) on the jobsites, etc. To collect and incorporate heterogeneous data both from offsite and onsite sources, the author: (1) developed a construction tasks (i.e., construction activities), resources (i.e., labor, materials, and equipment), and techniques (i.e., sensing techniques) integrated (ConTaRTI) ontology to classify construction site information; and (2) encoded construction sensing technique selection recommendations for monitoring construction site information into the proposed ConTaRTI ontology to help collect data.

The proposed ConTaRTI ontology offers a novel way to classify construction information that needs to be collected, measured, and detected on the construction site, it also provides sensing technique recommendations to guide methods and tools selection for the data collection on specific construction tasks and resources. It demonstrates a new method by linking construction site information with their data collection methods to support information management. The quantitative and qualitative evaluation results of the proposed ontology demonstrate that it is promising to be used in the construction domain to support decision-makings in sensing technique selection for data collection and information management.

Ontology Development

The term “Ontology” was firstly developed in 1613 by two philosophers independently, and it was firstly recorded in the Oxford English Dictionary in English in 1721 (Smith 2003). Ontology aims to simplify the point of view to represent something for specific purpose, which is a straightforward specification of an abstract (Guarino et al. 2009; Khan and Luo 2002). It defines a list of terms (i.e., concepts), the relationships among them, and the axioms (i.e., definitions of concepts and relationships, and their constraints), which are coded in the hierarchal structure (El-Gohary and El-Diraby 2010). Concepts define the “things’ (e.g., entities and families) either abstractly or concretely in the domain of interest. An entity represents an action, actor, product, resource, project, or mechanism, which has an attribute, a modality, and is a member of a family. An entity is controlled by a constraint. The affiliations between entities and families are defined by modalities (El-Gohary and El-Diraby 2010). Concepts in the ontology are associated with three relationships: is-a, part-of, and cross-concept relationships. Is-a relationship is also known as subsumption relationship, which is developed for the specialization of a super-concept into specialized sub-concept. Part-of relationship is known as partonymy relationship, which is developed for decomposing a concept into corresponding parts and structuring processes into patronymic hierarchies. Cross-concept relationship represents non-hierarchical semantic links between concepts, which emphasizes the reason of each link.

There are five main steps in the general procedure of ontology development, including: (1) define purpose and scope of the ontology; (2) build classes and class hierarchy in the ontology; (3) define relationships between classes; (4) implement ontology; and (5) evaluate ontology (Noy and McGuinness 2021; Xu and Cai 2021). In this dissertation, the author developed a ConTaRTI ontology to demonstrate the connections between construction site information and their corresponding sensing techniques for jobsite sensing guidance and data collection. It aims to provide sensing technique recommendations and further support construction information management. This purpose and scope dominate the represented information in the ontology (i.e., construction site information and sensing techniques), which will be demonstrated and classified in a hierarchical way. In addition, the recommendations regarding sensing technique selections based on different construction site information are enumerated based on referenced literature. Figure 42 illustrates the ConTaRTI ontology development procedure. In Figure 42, the purpose of the proposed ontology aims to fulfill the construction application (i.e., sensing technique recommendation provision), which determines the structure of the proposed ontology and helps define the classes and class hierarchy in it. The author conducted literature review regarding both construction site information and sensing techniques for data collection, which help define the concepts and their relationships between them. The proposed ConTaRTI ontology is encoded in the Protégé (version 5.5.0) using Web Ontology Language (OWL) (Figure 43). Protégé is an open-source ontology development editor, which is used to build knowledge-based intelligent systems (Gennari et al. 2003). OWL is a knowledge representation language for processing information in a computer rather than only presenting information to human (McGuinness and Van Harmelen 2004). The ConTaRTI ontology will be evaluated from quantitative and qualitative perspectives, which will be performed iteratively to improve the ontology.

Construction tasks and resources together with their corresponding sensing techniques for data collection provide the main theme for the ConTaRTI ontology development. Additionally, it could be used to collect jobsite data and further support construction information management. The ConTaRTI ontology would not be the "only one" information management model, because "there is no "perfect" ontology and no "optimum" classifications or concept hierarchies" according to El-Gohary and El-Diraby (2010).

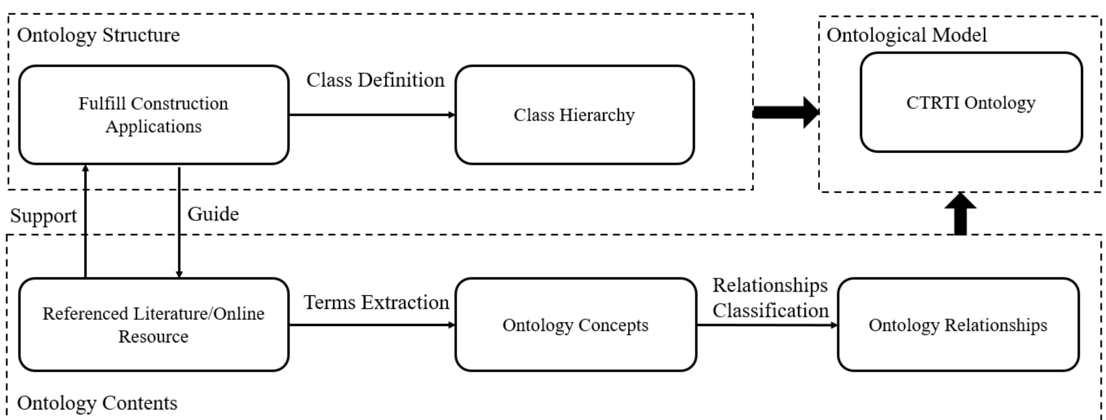


Figure 42. ConTaRTI ontology development process.

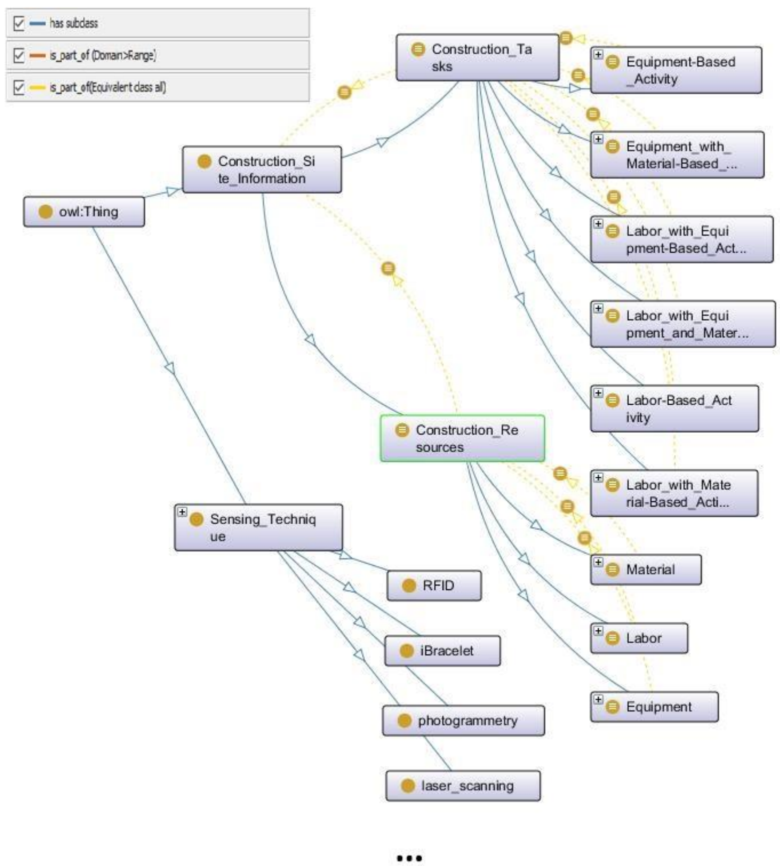


Figure 43. ConTaRTI ontology (network components module) structure (partial).

ConTaRTI Ontology Concepts. The proposed ConTaRTI ontology aims to capture construction site information (i.e., tasks and resources), and provide recommendations regarding sensing technique selections to specific construction site information for data collection. Therefore, it could be used to manage sensing techniques to support various construction applications on the construction site to facilitate information management (e.g., material tracking). Accordingly, at the highest level, the ConTaRTI ontology includes two main parts: construction site information and sensing techniques, which contribute to the use of the ConTaRTI ontology for jobsite sensing guidance. Construction site information is categorized into two main families: construction resources and tasks, which include labor, materials, equipment (El-Diraby et al. 2005), and their related activities on the construction sites, respectively. Sensing techniques mainly focuses on construction jobsite sensing techniques (e.g., passive infrared sensor) to support data collection. At the following level in the ConTaRTI ontology, construction tasks include six types of construction activities based on the use of different construction resources: labor-based, equipment-based, labor with equipment-based, labor with material-based, labor with equipment and material-based, and equipment with material-based activities. In addition, construction resources capture construction labor, materials, and equipment categories. In each category, the specific terms (e.g., walking from labor-based activity category, excavator from equipment category, and IMU from sensing technique category) are collected based on referenced literature in the context of construction jobsite data collection using sensing techniques.

ConTaRTI Ontology Relationships. In the ConTaRTI ontology, the "part-of" relationship is developed based on the nature of the construction site information and the data collection requirement. For example, construction tasks and resources are two parts of the construction site information, which contain the objects and activities that need to be detected, collected and measured for data collection purpose. Similarly, "Is-a" relationship demonstrates the connection between sub-concept and its super-concept. For instance, walking is one type of labor-based activities, which shares the same concept level with sitting and hand washing, which are also labor-based activities in the ConTaRTI ontology. Meanwhile, the "cross-concept" relationship is assigned based on literature to provide the recommendations regarding sensing technique selections. For example, tri-axial accelerometer will be recommended based on the ConTaRTI ontology for detection of sitting type of labor-based activity, based on reference Chen et al. (2008).

Ontology Implementation and Experimental Results Analyses

The ConTaRTI ontology was developed based on the nature of the construction resources and data collection needs of construction tasks on the jobsite, which covers construction site information that needs the sensing techniques to collect, including (1) resources: labor, materials, and equipment; and (2) tasks: labor-based activities, equipment-based activities, labor with equipment-based activities, labor with material-based activities, labor with equipment and material-based activities, and equipment with material-based activities. The corresponding sensing techniques for each construction resource and task were incorporated into the ontology and assigned to the specific resource and/or task. All above-mentioned information of the proposed ConTaRTI ontology was developed and encoded in the Protégé (version 5.5.0) using OWL. Then it was implemented with a user-friendly interface. For the developed ontology interface, Python programming language (Python 3.5.3) (e.g., tkinter package, SQLite library) was used for implementation.

The method for implementing the proposed ConTaRTI ontology includes five main steps (Figure 44). Step 1: Construction Tasks and Resources Information Development – This step defines the content in the ontology and classifies construction site information into different categories to support ontology development, which contains construction tasks (i.e., construction activities), and resources (i.e., labor, materials, and equipment). Step 2: Construction Sensing Techniques Information Development – This step lists the sensing techniques that are used to collect corresponding construction site information in different categories in Step 1. The selected sensing techniques were involved based on literature, which provides evidence to support the further sensing technique recommendation provisions in Step 3. Step 3: Technical Recommendation regarding Sensing Technique Selection – This step bridges the selected information in the ontology in Step 1 and their corresponding sensing technique information in Step 2 to help data collection for jobsite sensing guidance. Step 4: Ontology Integration – This step incorporates the defined construction site information in Step 1, sensing techniques in Step 2, and their relationships in Step 3, then implements them into an ontology-based user-friendly interface for guiding jobsite data collection. The developed interface makes the provision of jobsite sensing guidance one step closer to full automation to support decision-makings in the construction domain. In the interface, the corresponding sensing technique(s) for the specific type of construction site information will be provided based on the user selection of specific task (i.e., construction activity) or resource (i.e., labor, material, and equipment) in the ConTaRTI ontology. Step 5: Ontology Evaluation – This step evaluates the developed ontology from quantitative and qualitative perspectives. The evaluation results will be used iteratively to improve the ontology (i.e., refinement and development).

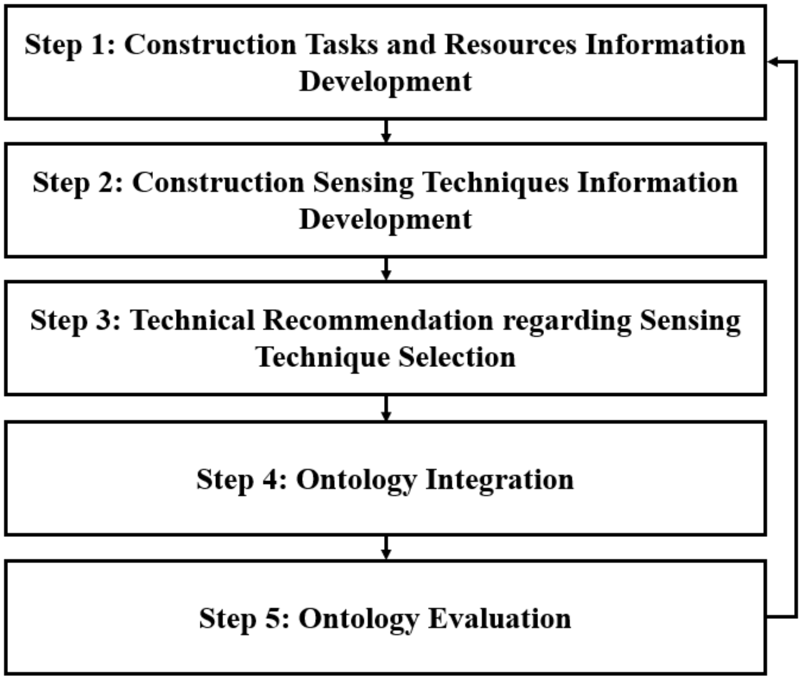


Figure 44. Method for ConTaRTI ontology implementation.

Step 1: Construction Tasks and Resources Information Development. The developed ConTaRTI ontology mainly covers three areas: (1) construction site information; (2) sensing techniques information; and (3) their relationships. For construction site information, the ConTaRTI ontology focused on two categories: (1) construction tasks (i.e., activities); and (2) resources (i.e., labor, materials, and equipment). Accordingly, construction resources include labor (e.g., construction worker), equipment (e.g., excavator), and materials (e.g., concrete). In addition, construction tasks contain all the resource-related activities, including labor-based activities (e.g., sitting), equipment-based activities (e.g., tower crane hook moving), labor with equipment-based activities (e.g., welding), labor with material-based activities (e.g., inspection of a weld), labor with equipment and material-based activities (e.g., concrete truck pouring concrete), and equipment with material-based activities (e.g., tower crane load concrete). The ConTaRTI ontology covers major types of information on the construction jobsites that needs the support by sensing techniques to help collect data, therefore, it could be used to support different applications (e.g., equipment tracking) to further support information management on the jobsite.

Step 2: Construction Sensing Techniques Information Development. With the improvement of the sensing techniques in the construction domain, there are more opportunities to fulfill different needs and construction operations during different phases of the life cycle of a building (Vähä et al. 2013). Sensing techniques play an important role for transferring traditional manual data collection method to an automated one to support business operations, such as site conditions monitoring, equipment and material management, worker safety, and facility management, among others (Ellis 2020). Accordingly, to facilitate data collection on the construction jobsite, the sensing techniques are incorporated into the ConTaRTI ontology to fill the gap. In the ConTaRTI ontology, the construction tasks and resources with their corresponding sensing techniques for data collection follow one-to-one and/or one-to-many relationships. All the sensing techniques in the ConTaRTI ontology were selected based on literature, the literature provides both the data source and specific reference information, which demonstrates the relationships between sensing techniques and the corresponding construction site information for which to collect data.

Step 3: Technical Recommendation regarding Sensing Technique Selection. In this step, the relationships between the construction tasks and resources information that were developed in Step 1 and corresponding types of sensing techniques that were developed in Step 2 are defined and encoded into the ontology. For example, the recommendation of the Crossbow MICA2s with sensor board MTS310CA and tri-axial accelerometer will be provided based on the ConTaRTI ontology to collect data for walking type of labor-based activity (Yin et al. 2008; Chen et al. 2008). After linking the construction tasks and resources with their data collection sensing techniques, the two parts of the ConTaRTI ontology have been integrated.

Step 4: Ontology Integration. In this step, the ConTaRTI ontology is encoded in OWL using Protégé. To make it easy to support jobsite sensing guidance, an ontology-based user interface is developed to support the use of the ontology (Figure 45). When running the interface, users could select specific terms of construction tasks or resources in different categories, then press the corresponding button regarding different categories, the sensing technique recommendations with their reference will be demonstrated in the text display box in different colors. Figure 45 illustrates the ontology-based user interface with zoomed-in looks. In Figure 45, the sensing technique Crossbow MICA2s with sensor board MTS310CA and tri-axial accelerometer with reference is provided for walking in the labor-based activity category (pink color).

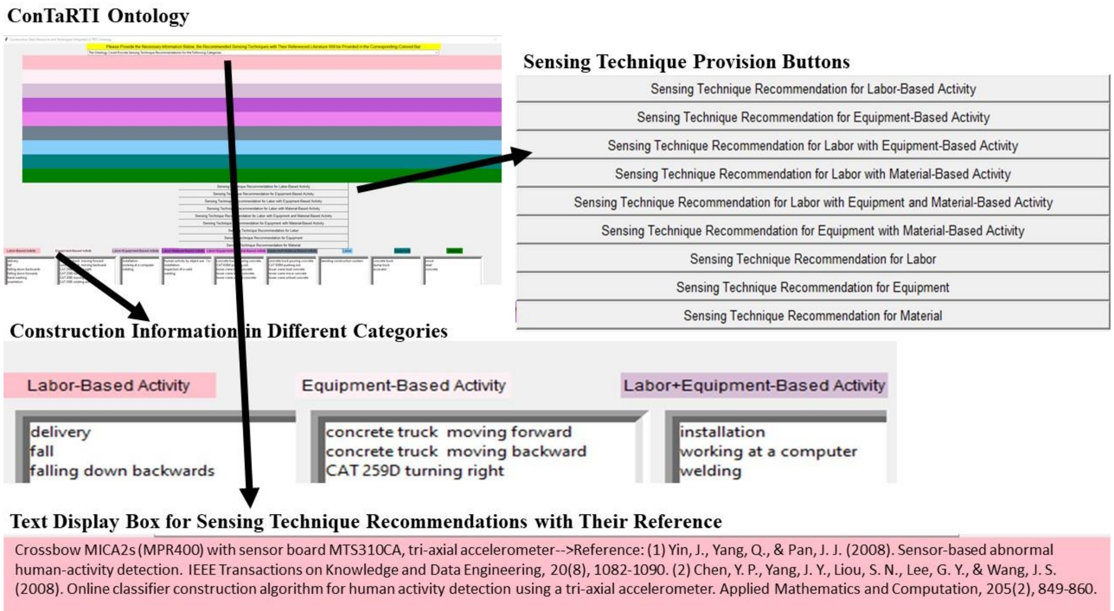


Figure 45. Ontology-based user interface.

Step 5: Ontology Evaluation. Currently, ontologies are widely used for representing knowledge as the foundation for Semantic Web (Antoniazzi and Viola 2019). Because the ontologies are expected to be reused in various domains, it is important to evaluate the ontologies in a scientific way (Raad and Cruz 2015). Based on Hlomani and Stacey (2014), quality and correctness are the two important metrics to evaluate the ontologies as a reference model, in which several criteria are considered, including conciseness, accuracy, adaptability, completeness, computational efficiency, clarity, and consistency (ElHassouni et al. 2020). Based on Raad and Cruz (2015), there are four methods to evaluate an ontology, which include gold standard-based methods, corpus-based methods, task-based methods, and criteria-based methods. Gold standard-based methods are the most straight-forward, they are also named as ontology alignment or ontology mapping (Ulanov 2010). In terms of using the gold standard-based methods, the comparison between the developed ontology and a reference ontology is procedurally conducted. Corpus-based methods evaluate the coverage of the developed ontology for a specific domain, they are the data-driven methods. When using the corpus-based methods, the comparison between the proposed ontology and a domain specific text corpus is conducted. Task-based methods assess the improvement to a certain task when using the proposed ontology, which only evaluate the performance of the ontology for a specific task without considering its structural characteristics. Task-based methods are usually used to evaluate the adaptability of an ontology. Criteria-based methods assess the adherence of the proposed ontology to a specific criterion. Table 18 summarizes different criteria for each ontology evaluation method, in which three levels (i.e., high, medium, and low) are assigned to the corresponding criterion in different methods (Raad and Cruz 2015).

Table 18. An Overview of Ontology Evaluation Methods.

	Gold Standard-Based Approaches	Corpus-Based Approaches	Task-Based Approaches	Criteria-Based Approaches
Accuracy	High	High	Low	Medium
Completeness	High	High	Medium	Low
Conciseness	High	High	Medium	Medium
Adaptability	Medium	Low	High	Medium
Clarity	Medium	Medium	Medium	High
Computational Efficiency	Low	Low	High	High
Consistency	Medium	Medium	High	High

Experimental Test

An experiment was conducted to evaluate the developed ConTaRTI ontology using task-based method, in which the proposed ontology was implemented with an interface to perform the assigned task. Accordingly, a given task was assigned to the ontology, that is, to provide recommendations regarding sensing technique selection for specific construction information (i.e., construction resources and tasks) data collection. Figure 46 demonstrates an example procedure of using the ConTaRTI ontology. In addition, the ontology evaluation was performed based on the procedure in Figure 46. Firstly, a user could select specific construction resources and tasks in different categories (e.g., labor-based activity). Then, the user pressed the corresponding button (e.g., Sensing Technique Recommendation for Labor-Based Activity), the sensing technique selection recommendation with its referenced literature would be provided in the text display box with the same color as the name of the selected category (e.g., pink for Labor-Based Activity).

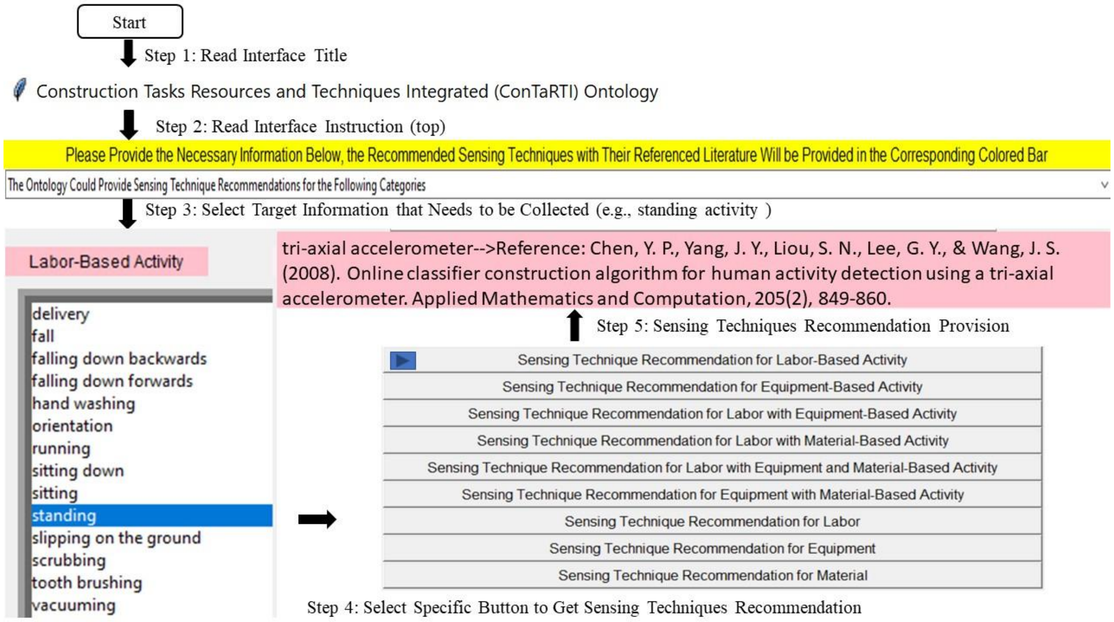


Figure 46. Ontology-based interface explanation with an example.

Evaluation

In the dissertation, task-based method is used to evaluate if the proposed ontology could provide recommendations regarding sensing technique selection appropriately, for data collection of specific construction site information. In this dissertation, there are three criteria considered for ontology evaluation (Raad and Cruz 2015): adaptability, computational efficiency, and consistency, which represent the criteria that are well covered by task-based ontology evaluation methods (Table 18).

In this dissertation, computational efficiency and consistency are used for quantitative analysis, and adaptability is used for qualitative analysis. Based on reference Raad and Cruz (2015), “Computational efficiency measures the ability of the used tools to work with the ontology.” Accordingly, the computational efficiency demonstrates the time consumption with and without using the ConTaRTI ontology, which is reflected/implemented with a user-friendly interface, to obtain sensing technique selection recommendations. With the use of the implemented ConTaRTI ontology, users only need to select the corresponding button to get sensing technique recommendations backed by referenced literature. On the contrary, without using the implemented ConTaRTI ontology, the users need to either browsing online or checking the book or other resources to get the sensing technique recommendations, which is time consuming and labor-intensive. The evaluation process of the computational efficiency was conducted by three independent researchers, in addition, each of them randomly tested twenty-five construction tasks and/or resources in the ConTaRTI ontology, then calculated the time spent for each of the twenty-five selections in order to get the average time consumption. The average time consumption when using the ConTaRTI ontology to get sensing technique recommendations was 4.664 seconds (standard deviation = 1.36), meanwhile, the average time consumption was 5.489 minutes (standard deviation = 73.45) without the use of the ConTaRTI ontology. Figure 47 shows the line chart of computational efficiency testing results. In Figure 6, the time consumption with the use of ConTaRTI ontology (i.e., blue line) is much less than without using the ontology (i.e., red line). In addition, the time consumption with the use of ontology is much more stable than without using it in the computational efficiency testing procedure. Table 19 demonstrates the computational efficiency testing results. It shows that the time consumption efficiency improvement achieves 98.58% when using the ConTaRTI Ontology. It demonstrates that the proposed ConTaRTI ontology is promising to be used in providing sensing technique recommendations for construction site information in an efficient way.

Table 19. Evaluation Results of the Computational Efficiency.

Method	Without the Use of the ConTaRTI Ontology	With the Use of the ConTaRTI Ontology	Evaluation Result
Computational Efficiency	Average 5.489 minutes	Average 4.664 seconds	Improved by 98.58%

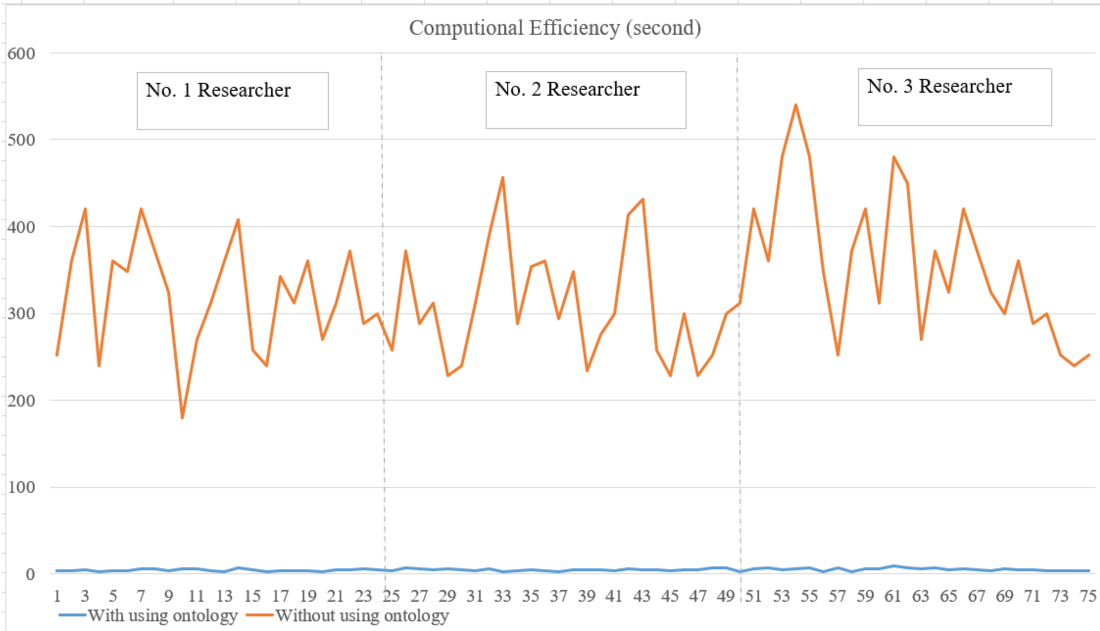


Figure 47. Line chart of computational efficiency testing results.

Adaptability illustrates how far the ConTaRTI ontology is anticipated to apply to different tasks/applications/scenarios (Raad and Cruz 2015). Therefore, the author considered other potential applications of the ConTaRTI ontology in several broad areas (e.g., education, commercial, and research areas), such as: (1) illustrating sensing techniques recommendations for specific construction site information, which can be used as a digital education tool to motivate students' learning for education innovation (i.e., education purpose); (2) serving commodity purchase analysis from sensor selection perspective for construction contractors in mitigating inadequate budget (i.e., commercial purpose); and (3) providing research tool guidance for target construction site applications in an efficient way, including safety management, construction worker monitoring, and smart construction, among others (i.e., research purpose). It provides the conceptual foundation for the anticipated tasks. In addition, because the proposed ConTaRTI ontology was implemented with a user-friendly interface, in which the two types of information (i.e., construction site information and sensing techniques) and their relationships are encoded with Python programming language. Its structure can be used directly and the contents are easy to be adapted to other applications, such as providing recommendations regarding project delivery methods based on different types of projects and organization structures, only the corresponding adjustments for ontology concepts are needed to fulfill the purpose. For instance, within the same structure of the ConTaRTI ontology, the two main parts (i.e., construction information and sensing techniques) could be replaced with different types of project and organization structures, and project delivery methods, respectively. Then the relationships between them could be assigned based on referenced literature accordingly. Therefore, the ConTaRTI ontology provides structure foundation with matching relationships to support other tasks/applications.

Consistency demonstrates that the ontology does not contain or allow for any contradictions (Raad and Cruz 2015). In this dissertation, for the evaluation of consistency of the proposed ontology, an open-source reasoner, named HermiT (Motik et al. 2021), was used. HermiT is an OWL ontology reasoner, which determines if the ontology is consistent, and identifies subsumption relationships between classes. In this dissertation, the ontology was imported into Protégé, HermiT reasoner runs and evaluates the ontology, in which the majority of the ontology contents are consistent (95%). The ontology was fully consistent after minor revisions (100%).

Based on the evaluation results, the proposed ontology could provide the conceptual foundation for the anticipated tasks based on adaptability evaluation, achieved 98.58% improvement in computational efficiency comparing to the manual approach, and 100% in consistency, which demonstrate that the proposed ontology is promising and could be used for providing sensing technique selection recommendations to different construction resources and tasks, and further support construction information management.

5.3.2 Potential Ontology Application - Proposed Framework of Construction Applications Information Management

Obtaining different types of information throughout the entire life cycle of a project to support information management is an essential research topic of great interest in the AEC domain. To facilitate the process of managing construction information by leveraging and integrating different functions and applications, the author proposed an ontology-based construction applications information management framework (Figure 48), in which the textual procedural information extraction, sensing technique recommendation and selection, and information analysis application are integrated into one framework to support construction information management. There are three main levels in the proposed framework, which includes textual procedural information extraction (IE) (i.e., information level), sensing technique recommendation and selection (i.e., service level), and information analysis application for different tasks (i.e., application level). Therefore, in the proposed framework, construction information could be extracted, collected, and implemented based on the proposed ConTaRTI ontology. For example, firstly, planned execution steps could be extracted using textual IE from construction procedural document based on the ontology, which provides the guidance for execution steps on the construction sites. Then sensing technique selection recommendations will be provided based on the IE results and the developed ConTaRTI ontology, which provides the recommendations regarding how to collect onsite information (i.e., construction resources and tasks) that is extracted from offsite sources (i.e., construction procedural documents). It helps data collection for further information comparison and analysis. Lastly, the collected data using recommended sensing techniques can be used to support different construction applications, such as inventory checking, and safety and health monitoring (Shults et al. 2019; Ahn et al. 2019). The proposed construction applications information management framework is supported by the newly developed construction tasks, resources, and techniques integrated (ConTaRTI) ontology, it illustrates a new method to integrate and leverage heterogeneous data for construction site information management.

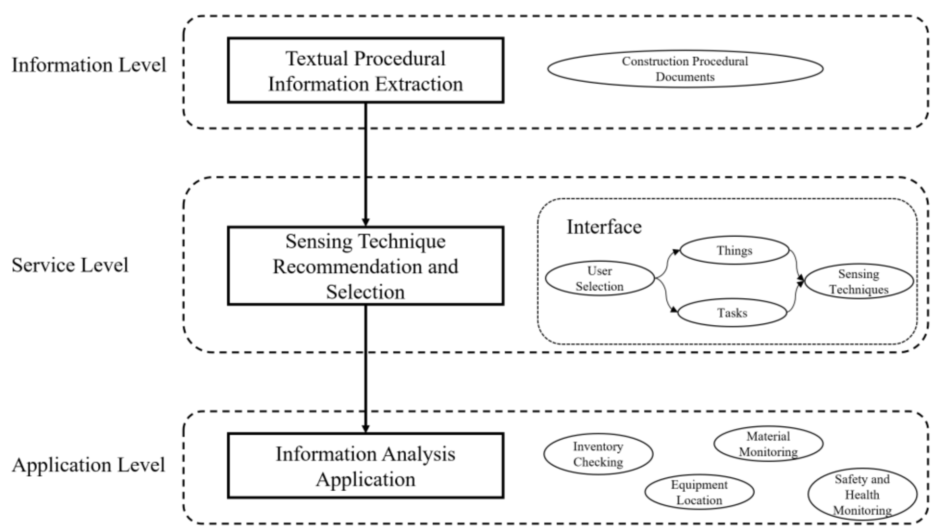


Figure 48. Proposed ontology-based construction applications information management framework.

CHAPTER 6 –CONCLUSION

A portion of this chapter was previously published by:

"A BIM Information Processing Framework to Facilitate Enriched BIM Applications." *Proc., ASCE Construction Research Congress*, ASCE, Reston, VA, accepted.

"An Integrated Framework to Support Construction Monitoring Automation Using Natural Language Processing and Sensing Technologies." *Proc., 2021 ASCE International Conference on Computing in Civil Engineering*, in press.

"Comparison of BIM Interoperability Applications at Different Structural Analysis Stages." In *Construction Research Congress 2020: Computer Applications* (pp. 537-545). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784482865.057

"BIM Interoperability for Structural Analysis." In *Construction Research Congress 2018: Construction Information Technology.:* https://ascelibrary.org/doi/abs/10.1061/9780784481264.046

"A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions." *Advances in Civil Engineering*, *2021*. https://doi.org/10.1155/2021/8824613

"Model Information Checking to Support Interoperable BIM Usage in Structural Analysis." In *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation* (pp. 361-368). Reston, VA: American Society of Civil Engineers. : https://doi.org/10.1061/9780784482421.046

"Semantic Rule-Based Construction Procedural Information Extraction to Guide Jobsite Sensing and Monitoring." *Journal of Computing in Civil Engineering*, 35(6), 04021026. DOI: 10.1061/(ASCE)CP.1943-5487.0000971.

"An Ontology-Based Interface to Guide Jobsite Sensing and Construction Tasks/Applications to Support Construction Information Management." (In Preparation)

6.1 Conclusion

6.1.1 Data Analysis at the Information Level

Interoperable data exchange is important in the architecture, engineering, and construction (AEC) domain because of: (1) the collaborative nature of the domain; and (2) the many differences in the tools and data formats used by different stakeholders. In this dissertation, the author conducted a preliminary literature review about BIM interoperability trying to identify topics and trends on the BIM interoperability problem with a focus on the structural analysis domain, from both the theoretic perspective and the application perspective. Based on the review and preliminary experimental analysis, research gaps were identified in the BIM interoperability with structural analysis area where future researches are recommended: (1) the need of better information coverage in the IFC schema; (2) the need of stronger IFC importation/exportation support in structural analysis software; (3) the lack of methods other than the "top-down" approach in representing model elements and tracking semantic changes of elements between different models; and (4) the lack of tools and methods in addressing model information distortion and geometric precision lost problems. Addressing these research gaps can improve interoperability of IFC-based BIM, and therefore facilitate information flow between different parties in the AEC domain with a central model/database, resulting in a simpler information flow pattern and less interoperability problems.

In addition, to be specific, information missing during model exportation from BIM structural analysis software is an important problem that needs to be solved to support BIM interoperability in the AEC domain. To address this problem, the author conducted a preliminary analysis of the information coverage among three structural analysis stages (i.e., intrinsic, extrinsic, and analysis stages) from text and IFC files exported from different structural analysis BIM software. The files exported from the same BIM model were compared in horizontal and vertical perspectives. The results showed that (1) models could be exported as text files and IFC files from BIM analysis software, (2) geometric, material, supports and load information could be exported both to the text files and IFC files from BIM analysis software, and (3) structural analysis results could not be exported from BIM analysis software directly neither to text nor to IFC files. With the anticipated full life cycle comprehensive information support goal of BIM for structural analysis, more research and development need to be performed to close the roundtrip information transfer loop for all intrinsic, extrinsic, and analysis results information.

Furthermore, the author analyzed and addressed BIM interoperability problems and used it to analyze BIM interoperability between architectural design and structural analysis. Six common project delivery methods were taken into account as the background context and a BPMN diagram was created based on the transfer and use of modelling information between architectural models and structural models in the architectural design and structural analysis processes. Six technical route segments were summarized to explain any BIM interoperability application between the architectural design and structural analysis processes. In the process and management dimension in the context of BIM interoperability application at the information analysis level, the proposed technical routes (Figure 11) with different combinations, and their applications to different project delivery methods provide new instruments for stakeholders in industry to use for supporting their decision making. Therefore, it enables the interaction between architects and structural engineers to be more efficient and therefore more frequent to contribute practical impact in a project process not only for a shorter schedule and faster information delivery but also for a better design and safer structure. All above-mentioned information analyses methods provide foundations to support BIM interoperability at the data process level.

6.1.2 Data Refining at the Process Level

To facilitate data interoperability, the author devised invariant material signatures and developed material signatures for three common construction materials. Then the author developed a formal material information representation and checking method in a systematic way to help solve the material information gap identified through the experiment. The advantage of the proposed material information representation and checking method was demonstrated in a comparative experiment with manual information transfer and checking through a case study. It shows that applying the proposed material information representation and checking method to a construction project could improve information exchange between the architectural models and the structural models for facilitating communication efficiency between architects and structural engineers, therefore bringing the time and cost benefits to the entire project delivery process.

In addition, to facilitate information management in the context of construction monitoring application, this dissertation presented a semantic, rule-based IE methodology for automated execution steps IE from construction procedural documents. A set of pattern matching-based IE rules and customized supplement extraction rules were used in IE processes. The extracted patterns were represented in terms of syntactic and semantic text features. A set of NLP techniques were utilized to select the syntactic features of the construction procedural documents. A construction procedural and data collection (CPDC) ontology was developed and used to select the semantic features, which represented execution steps in the procedural documents. In addition, it provides a new instrument for selecting sensing techniques to collect data on the jobsite. Semantic information element instances were extracted separately and sequentially to reduce the number of needed patterns for further use.

The proposed IE method was tested on execution steps of a set of open-source specifications. Comparing to a manually developed gold standard, 97.08% precision, 93.23% recall, and 95.12% F1 measure were achieved for execution steps IE. The high-performance indicates that the IE method is promising.

6.1.3 Data Processing at the Service and Application Level

In terms of leveraging BIM-related Information, this dissertation proposed an all-in-one-place information checking, provision, and application process (ICPAP) framework, which is implemented into a python-based user interface by integrating model information analysis, guided information provision, and information consumption application. An experiment of a 12-storey concrete IFC model was conducted to mainly test the framework at the material information level. The evaluation results of the proposed framework demonstrated that the proposed framework achieved information representation, checking, and extraction in a more efficient and accurate manner comparing to performing them manually. Therefore, the proposed framework could better leverage BIM-related model (e.g., IFC model) in helping: (1) information representation to facilitate communication between different software/platforms/systems/applications, (2) information checking to better understand and check the useful information in an accurate and efficient manner, (3) guided information provision to help provide customized recommendations and support decision-making in the AEC domain, and (4) information consumption application to better use and integrate the provided information in the construction applications.

Meanwhile, to integrate, analyze, and manage construction site information, the author proposed a new construction monitoring framework, which integrates NLP and sensing techniques (i.e., computer vision) for automatically monitoring construction jobsite based on construction procedural documents. The proposed framework consists of three main components: (1) a textual information extraction and processing model, which uses an NLP-based algorithm to extract information from procedural documents and process it automatically; (2) a label information extraction and processing model, which utilizes a deep learning computer vision algorithm to detect, analyze and process jobsite execution steps from sensed video on the construction jobsite; and (3) an integrated compliance checking model, which utilizes longest common subsequence algorithm to automatically match and check the similarity of the execution steps from the construction procedural document and the analyzed video. The proposed monitoring framework was experimentally tested in checking the execution steps of selected construction specifications and a corresponding synthesized video. Comparing to a manually developed gold standard, 83.33% recall, 71.43% precision, and 76.92% F1-measure in construction procedure compliance checking were obtained.

Similarly, the author also proposed an IE method-based general implementation framework of construction monitoring applications, which is named as construction procedural data integration (CPDI) framework. It provided a fully automated approach to monitor sequence of execution procedure for construction job sites. This dissertation mainly focused on the IE of execution steps from construction procedural documents. The proposed IE method in this dissertation presented a textual information extraction and processing model, which utilized Python algorithm to automatically extract information from textual data and processed it based on different situations such as time sequence relations to support CPDI framework.

This dissertation also presented a construction tasks, resources, and techniques integrated (ConTaRTI) ontology by incorporating construction site information, its corresponding sensing technique for data collection, and the relationships between them. It covers the major types of information on the construction site that may need the support by sensing techniques in data collection. In the ConTaRTI ontology, both the recommended sensing techniques and the corresponding referenced literature are provided to demonstrate the sensing technique selection recommendations, which can support the decision-makings in the construction domain in an efficient and accurate manner. The proposed ConTaRTI ontology was quantitatively and qualitatively evaluated using task-based approach to assess the adaptability, computational efficiency, and consistency. It demonstrates that the proposed ConTaRTI ontology is promising and could be implemented in the construction domain to help provide sensing technique selection recommendations regarding data collection methods for specific construction resources and tasks. In the meantime, the author proposed a ConTaRTI ontology application: an all-in-one-place construction applications information management framework, which integrates textual procedural information extraction, sensing technique recommendation and selection, and information analysis applications (e.g., inventory checking). The proposed framework can help integrate and leverage data from different construction stages, functions, and applications into one framework in an efficient and accurate manner.

In addition, the proposed ontology-based construction applications information management framework integrates different functions into one framework, which provides a potential knowledge model-based implementation to facilitate construction information management by integrating heterogeneous data and leveraging them in different construction applications.

6.2 Contributions to the Body of Knowledge

6.2.1 Data Analysis at the Information Level

This research is one of the first systematic explorations of BIM interoperability between architectural design and structural analysis that was targeted at supporting BIM interoperability research and development. This research contributes to technical routes by summarizing six route segments of BIM interoperability between architectural design and structural analysis. A combination of one or more route segments could form a closed loop for information transfer to support BIM interoperability, which is what the AEC industry ultimately needs. The technical route segments with different combinations for information transfer, and their applications to specific project delivery method provide new instruments to stakeholders in industry for efficient and accurate decision making. The gap analyses regarding information missing and information inconsistency between architectural models and structural models were conducted to find that in some situations, such as the technical route from proprietary architectural BIM to IFC and from IFC to proprietary structural analysis model, material information could be missing. The author developed gap analyses of material information between architectural models and structural models and proposed a new set of invariant material signatures and a corresponding material information representation and checking method. The proposed material information representation and checking method could improve information transfer between architectural design and structural analysis to support BIM interoperability in different project delivery methods. The case study results showed that the proposed method could improve information exchange efficiency between architectural design and structural analysis to facilitate BIM interoperability. In addition, the proposed method can be adapted to facilitate the information flow between any two stages of the lifecycle of a building or infrastructure (e.g., roadway, bridge, culvert) project (e.g., between pre-construction stage and post-construction stage to deal with the maintenance issues).

The impact of applying this research in the AEC domain could be far-reaching. This research provides a formal invariant signatures-based material information representation and checking method to support BIM interoperability. This method facilitates information exchange between architectural models and structural models, which helps improve the information transfer and coordination between architects and structural engineers and therefore the efficiency of the whole project. The proposed method can be extended and applied to other application phases and functions such as cost estimation, scheduling, and energy analysis.

6.2.2 Data Refining at the Process Level

BIM-based data processing methods that are developed in this dissertation, including invariant signature-based information representation, and MVD-based information checking algorithm, can be applied to the construction domain to support information analysis, information processing, and information applications in general.

At the data process level in the context of considering construction site information, this research contributes to the body of knowledge in three main ways. Firstly, this research offers a domain-specific, semantic NLP method that can assist in capturing domain-specific meanings from construction procedural documents. Construction procedural documents are important documents for contractors in the construction sites to guide on how to install objects and the desired level of quality. This work demonstrates an automated IE method to extract execution steps from construction procedural documents, which can be used for the proposed construction procedural data integration (CPDI) framework implementation, it would reduce the time, cost, and errors of the checking process in the construction site. Secondly, the proposed method provides a new information classification method based on a new construction procedural and data collection (CPDC) ontology, which links the planned procedure of construction documents with executed procedure that is collected from sensing techniques in the construction sites. In addition, it provides a new instrument for selecting sensing techniques on the jobsite to collect execution data. Thirdly, this research offers a novel way to include construction activities in the construction procedural documents that were seldom analyzed in the previous research (e.g., preparation surface and cleaning floor), but they are important source of information for the construction job sites.

The proposed IE method can be applied to integrate both textual information and activity information into one framework. In this research, a set of information extraction, information reorganization, and processing algorithms were prepared to effectively implement into the unified framework for automated monitoring

6.2.3 Data Processing at the Service and Application Level

The proposed ICPAP framework can be used to integrate and leverage different types of information from different phrases, stages, functions, and applications in the AEC domain to support various enriched BIM applications.

Similarly, the developed construction monitoring framework, and Construction Procedural Data Integration (CPDI) Framework enable the traditional construction monitoring application one step closer to an automated one. In addition, they offer a new way to monitor construction activities that were seldom analyzed (e.g., installation) in the previous research, in an automated fashion.

Furthermore, this dissertation incorporates construction site information and sensing techniques into a newly developed construction tasks, resources, and techniques integrated (ConTaRTI) ontology. The proposed ConTaRTI ontology includes construction resources (i.e., labor, materials, and equipment) and tasks (i.e., construction activities), and their corresponding sensing techniques for data collection. It can provide sensing technique recommendations based on specific construction site information. Thus it is implemented with a user interface to demonstrate the ontology purpose, which successfully demonstrated and integrated the construction tasks and resources, their corresponding sensing techniques for data collection, and relationships between them that are backed by referenced literature. It can be easily applied to the construction domain to provide sensing technique recommendations in an efficient and accurate way to support decision-makings. In addition, the ConTaRTI ontology could be used to select sensing techniques for different construction site information to help data collection, which could motivate students' learning and facilitate education innovation. Similarly, the ontology structure could be adopted for other tasks/applications, the contents can be easily adjusted and used for other tasks/applications (e.g., providing recommendations regarding project delivery methods based on different types of projects and organization structures). This dissertation also offers a novel framework to demonstrate a potential ConTaRTI ontology application by integrating textual procedural information extraction, sensing technique recommendation and selection, and information analysis application into one framework to support construction information management. It demonstrates a new approach to leverage and integrate heterogeneous data into one framework to facilitate construction information management.

6.3 Limitations and Future Work

The limitations and future work mainly focus on data processing methods, which are developed based on information analysis approaches and can be used to further support other proposed frameworks, systems, and applications in the AEC domain. For the proposed formal information representation and checking method, the author acknowledges the following limitation in its current shape. Although the proposed method was tested in representing and checking required material information for information transfer between an architectural model and a structural model, how it will perform in representing and checking other types of information, such as analysis results information, needs to be further explored. In future work, the author plans to expand the proposed method in representing and checking other types of information such as logistic information and in different interoperability scenarios such as between architectural design and energy simulation.

Similarly, three limitations of the proposed construction procedural IE method are acknowledged which the author plans to address in her future/ongoing research. (1) The proposed IE in this dissertation was only focused on extracting execution steps of construction procedural documents. It could be extended to support the checking of other types of requirements, such as material requirements; (2) The proposed method was only tested in checking execution steps of openings section in a set of construction procedural documents. As part of future/ongoing research work, the proposed method will be tested on more sections (e.g., finishes); (3) The proposed method was tested only on construction procedural documents. In future work, the proposed method will be extended to extract information from other types of contractual documents (e.g., inspection report). In addition, the author plans to integrate the IE method into scheduling applications by considering critical path method (CPM) and activity-on-node (AON) network diagram.

In terms of the ontology-based sensing technique guidance and application, three limitations are acknowledged, which the author plans to address in her future/ongoing work: (1) The proposed ontology focused on providing construction sensing technique recommendations for construction resources and tasks on the jobsite. It could be extended to provide sensing techniques recommendations for other types of construction information, such as weather station information for meteorological monitoring; (2) The proposed ontology focused on providing construction sensing technique recommendations. It could be extended to provide other types of recommendations, such as green building material selection based on construction site weather scenarios, etc.; and (3) The proposed ontology-based construction applications information management framework only considers textual procedural information extraction, sensing technique recommendation and selection, and information analysis application. As part of the future/ongoing research work, the author proposes to incorporate and implement other types of functions/applications into the framework, such as stakeholders' communications.

REFERENCES

Abbas, A., Din, Z. U., & Farooqui, R. (2016). Integration of BIM in construction management education: an overview of Pakistani Engineering universities. Procedia Engineering, 145, 151-157. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1877705816300388

Ahmed, S. (2019). A review on using opportunities of augmented reality and virtual reality in construction project management. Organization, Technology and Management in Construction: an International Journal, 11(1), 1839-1852. Retrieved from: https://content.sciendo.com/view/journals/otmcj/11/1/article-p1839.xml

Ahn, C. R., Lee, S., Sun, C., Jebelli, H., Yang, K., and Choi, B. (2019). Wearable sensing technology applications in construction safety and health. Journal of Construction Engineering and Management, 145(11), 03119007. DOI: 10.1061/(ASCE)CO.1943-7862.0001708.

Al Qady, M.A., and Kandil, A. (2010). "Concept relation extraction from construction documents using natural language processing." J. Constr. Eng. Manage., 136(3), 294-302.

Ajayi, O. G., Palmer, M., & Salubi, A. A. (2018). Modelling farmland topography for suitable site selection of dam construction using unmanned aerial vehicle (UAV) photogrammetry. Remote Sensing Applications: Society and Environment, 11, 220-230. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2352938518301058?casa_token=1Y-t4ks3kOMAAAAA:i-Zp1pOGuEwmPZFY6CRuiqWMR8xULT42ANVWqgqN7X5Cobm3ZAwQxw1STHm_zrPNqp0lfy1M0A

Akanbi, T., Zhang, J., & Lee, Y. C. (2020). Data-Driven Reverse Engineering Algorithm Development Method for Developing Interoperable Quantity Takeoff Algorithms Using IFC-Based BIM. Journal of Computing in Civil Engineering, 34(5), 04020036. Retrieved from: https://ascelibrary.org/doi/full/10.1061/(ASCE)CP.1943-5487.0000909?casa_token=s5MklwQuUU4AAAAA:Bv5qqs7BM1xgNlF9sMzyckuCKx1e3pYhGQWLcz4mBnnlAURh_ynKogNHV7NF37bt1ZAml5SGIiiy

Akhavian, R., & Behzadan, A. H. (2016). Smartphone-based construction workers' activity recognition and classification. Automation in Construction, 71, 198-209. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580516301698?casa_token=R5-pgbG5s54AAAAA:Z4njHLReKedxrZhWKRhCcxCWm9d-Kq5F1kxOdIxV3PhULhYRZ2YBRAVmiAWqhfrNbxHCQT0zUg

Akanbi, T., and Zhang, J. (2021). "Design Information Extraction from Construction Specifications to Support Cost Estimation." Journal of Automation in Construction, 131(November 2021), 103835.

Akanbi, T., and Zhang, J. (2022). "Framework for Developing IFC-Based 3D Documentation from 2D Bridge Drawings." Journal of Computing in Civil Engineering, 36(1), 04021031.

Akanmu, A., and Zhang, J. (2016). "An adaptive automated monitoring of construction activities using swarm nodes." Proc., 33rd International Symposium on Automation and Robotics in Construction, I.A.A.R.C., iaarc.org.

Aldegeily, M., Zhang, J., Hu, Y., & Shao, X. (2018). From architectural design to structural analysis: a data-driven approach to study building information modeling (BIM) interoperability (Doctoral dissertation, Western Michigan University). Retrieved from: http://ascpro0.ascweb.org/archives/cd/2018/paper/CPRT152002018.pdf

AMBICO. (2020). Retrieved from: https://www.arcat.com/sdspecs/htm04/08_11_00abl.htm

Anwar, N., Izhar, M. A., & Najam, F. A. (2018, July). Construction monitoring and reporting using drones and unmanned aerial vehicles (UAVs). In The Tenth International Conference on Construction in the 21st Century (CITC-10) (pp. 2-4). Retrieved from: https://www.researchgate.net/profile/Naveed-Anwar-5/publication/326264559_Construction_Monitoring_and_Reporting_using_Drones_and_Unmanned_Aerial_Vehicles_UAVs/links/5b42f727aca2728a0d6545ea/Construction-Monitoring-and-Reporting-using-Drones-and-Unmanned-Aerial-Vehicles-UAVs.pdf

Antoniazzi, F., and Viola, F. (2019). Building the semantic web of things through a dynamic ontology. IEEE Internet of Things Journal, 6(6), 10560-10579.

ARCAT. (2020). Retrieved from: https://www.arcat.com/content-type/spec/openings-08

Artstein, R. (2017). Inter-annotator agreement. In Handbook of linguistic annotation (pp. 297-313). Springer, Dordrecht. Retrieved from: http://ron.artstein.org/publications/inter-annotator-preprint.pdf

Asadi, K., & Han, K. (2018). Real-time image-to-BIM registration using perspective alignment for automated construction monitoring. In Construction Research Congress (Vol. 2018, pp. 388-397). Retrieved from: https://www.researchgate.net/profile/Khashayar_Asadi2/publication/324174295_Real-Time_Image-to-BIM_Registration_Using_Perspective_Alignment_for_Automated_Construction_Monitoring/links/5ac3f5ea458515564eaf2070/Real-Time-Image-to-BIM-Registration-Using-Perspective-Alignment-for-Automated-Construction-Monitoring.pdf

Bae, H., Golparvar-Fard, M., & White, J. (2013). High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications. Visualization in Engineering, 1(1), 1-13. Retrieved from: https://viejournal.springeropen.com/articles/10.1186/2213-7459-1-3

Bangaru, S. S., Wang, C., & Aghazadeh, F. (2020). Data Quality and Reliability Assessment of Wearable EMG and IMU Sensor for Construction Activity Recognition. Sensors, 20(18), 5264. Retrieved from: https://www.mdpi.com/1424-8220/20/18/5264

Bank, L. C., McCarthy, M., Thompson, B. P., & Menassa, C. C. (2010, December). Integrating BIM with system dynamics as a decision-making framework for sustainable building design and operation. In Proceedings of the First International Conference on Sustainable Urbanization (ICSU) (pp. 15-17). Retrieved from: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.455.1368&rep=rep1&type=pdf

Beazley, S., Heffernan, E., & McCarthy, T. J. (2017). Enhancing energy efficiency in residential buildings through the use of BIM: The case for embedding parameters during design. Energy Procedia, 121, 57-64. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1876610217334410

Braila, N., Panchenko, N., & Kankhva, V. (2021). Building Information Modeling for existing sustainable buildings. In E3S Web of Conferences (Vol. 244, p. 05024). EDP Sciences.

Bristol Brewing Company. (2014). Retrieved from: https://www.peakradar.com/event/bristol-presents-karma-hour-benefitting-csi/ (Nov. 11th).

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). International journal of project management, 31(7), 971-980. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0263786312001779?casa_token=CeuYxe9pp44AAAAA:OcgSaXUPi7OqbtbxOmcS8thOTWz1xnKiYzGSiVugjNC1RglR6nwiq1R25XSEIHGB8e2msJgQRA

Caldas, C. H., Soibelman, L., & Han, J. (2002). Automated classification of construction project documents. Journal of Computing in Civil Engineering, 16(4), 234-243. Retrieved from: https://ascelibrary.org/doi/abs/10.1061/(ASCE)0887-3801(2002)16:4(234)?casa_token=8DEWc1ZRgTUAAAAA:-gXIsV8oip7NQDOOKr46TFgmSUZGUJzNiTbghBYFDfIsbXiTABjtGJTW6LzXTQuhVy0VSp8eBeNe

Caldas, C. H., and Soibelman, L. (2003). Automating hierarchical document classification for construction management information systems. Automation in Construction, 12(4), 395-406. doi:10.1016/S0926-5805(03)00004-9.

Chen, Y. P., Yang, J. Y., Liou, S. N., Lee, G. Y., and Wang, J. S. (2008). Online classifier construction algorithm for human activity detection using a tri-axial accelerometer. Applied Mathematics and Computation, 205(2), 849-860. https://doi.org/10.1016/j.amc.2008.05.099.

Chi, H. L., Wang, X., & Jiao, Y. (2015). BIM-enabled structural design: impacts and future developments in structural modelling, analysis and optimisation processes. Archives of computational methods in engineering, 22(1), 135-151. Retrieved from: https://link.springer.com/article/10.1007%2Fs11831-014-9127-7

Chi, H. L., Kang, S. C., & Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. Automation in construction, 33, 116-122. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580513000022?casa_token=IF7Yu2ZX5ZMAAAAA:kWkzgkMkm6GmdY3aTQVR1kWIDunemCYiify-3c-qDaqaGhoUgg93Lya002WJUdUzZRZbOSgSEw

Chen, K., and Lu, W. (2019). Bridging BIM and building (BBB) for information management in construction. Engineering, Construction and Architectural Management. https://doi.org/10.1108/ECAM-05-2018-0206.

Ciribini, A. L. C., Ventura, S. M., & Paneroni, M. (2016). Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project. Automation in construction, 71, 62-73. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580516300449?casa_token=HmEnKSfxvHsAAAAA:2j60H6qfBE9bIbkC0QLEB3y8bUp-86UjsNDBrCer8EPjcUI3aXnPoubgWLCpLz3NUerv0o_4ZA

Clevenger, C. M., Ozbek, M., Glick, S., & Porter, D. (2010, February). Integrating BIM into construction management education. In EcoBuild Proceedings of the BIM-Related Academic Workshop (Vol. 8). Retrieved from: https://d1wqtxts1xzle7.cloudfront.net/33979837/Clevenger__Integrating_BIM_into_CM.pdf?1403087831=&response-content-disposition=inline%3B+filename%3DIntegrating_BIM_into_Construction_Manage.pdf&Expires=1615351403&Signature=Ve1guLDmO13gnkUOh-7-Jzj~nfDip3F9BR7652gTLwCl3NYZlB5uDhwtfS-dZcxMLHC-~cz5SJgV6HYc9fg8DISlgV-ZihzD~pI2vlbzyJF2-YggLssXFlrUHCxEts-ARyvpJKZ6AEv05tEfpTb~ImXK~J4BtOpiF2RwSwQA-09~iaThJCekHj1LSf9-E7CrTHrJX1Ds~TfMyolF9XMOZskMjcPFg23wKNi1Kq-ISWpYVdFCBCx~OFuQipV8~VxFGpL-Ud-hKg4WXABao9zsK9tiRUOXRvhXqiorNEnpXD4VQ6MyOQ~beqInr9Dm0FZ9KCMYApm-Y6uJZOeLhQl5KA__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

Cline Doors. (2020). Retrieved from: https://www.arcat.com/sdspecs/htm04/08_11_16cli.htm.

Clough, R. H., Sears, G. A., Sears, S. K., Segner, R. O., & Rounds, J. L. (2015). Construction contracting: A practical guide to company management. John Wiley & Sons. Retrieved from: https://books.google.com/books?hl=en&lr=&id=Cdy5BgAAQBAJ&oi=fnd&pg=PA1&dq=Construction+contracting:+A+practical+guide+to+company+management&ots=otq6XwU4a1&sig=KnazaHo_tsXLXsf9miaon6CzU-k#v=onepage&q=Construction%20contracting%3A%20A%20practical%20guide%20to%20company%20management&f=false

Coluccia, A., Fascista, A., Schumann, A., Sommer, L., Ghenescu, M., Piatrik, T., ... & González, I. (2019, September). Drone-vs-bird detection challenge at ieee avss2019. In 2019 16th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS) (pp. 1-7). IEEE. Retrieved from: https://ieeexplore.ieee.org/document/8909876

CSI. (2017). Construction Specifications Institute. Retrieved from: https://www.csiresources.org/institute/csi-history

Daniotti, B., Pavan, A., Spagnolo, S. L., Caffi, V., Pasini, D., & Mirarchi, C. (2020). Benefits and Challenges of BIM in Construction. In BIM-Based Collaborative Building Process Management (pp. 143-165). Springer, Cham. Retrieved from: https://link.springer.com/chapter/10.1007/978-3-030-32889-4_6

Deng, X. Y., & Chang, T. Y. P. (2006). Creating structural model from IFC-based architectural model. In Joint International Conference on Computing and Decision Making in Civil and Building Engineering (No. 557, pp. 3687-3695). Retrieved from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.232.2379&rep=rep1&type=pdf

Dib, H., Adamo-Villani, N., and Issa, R. (2011). "A GIS-Based Integrated Information Model to Improve Building Construction Management: Design and Initial Evaluation." CONVR 2011, Weimar, Germany.

Dunbarton. (2020). Retrieved from: https://www.arcat.com/sdspecs/htm04/08_11_10dbc.htm

Eastman, C., Lee, J. M., Jeong, Y. S., & Lee, J. K. (2009). Automatic rule-based checking of building designs. Automation in construction, 18(8), 1011-1033. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580509001198?casa_token=-SUjAVVkGeAAAAAA:EOaF2Df_cnmfV1on5hjfS4PYmRQDEnLYw5_VwPF4zWrq8ZtE1TFrG6Qg60EdbIgMACMEbkS_2A

El-Diraby, T. A., Lima, C., and Feis, B. (2005). Domain taxonomy for construction concepts: toward a formal ontology for construction knowledge. Journal of computing in civil engineering, 19(4), 394-406. DOI: 10.1061/(ASCE)0887-3801(2005)19:4(394)

El-Gohary, N. M., and El-Diraby, T. E. (2010). Domain ontology for processes in infrastructure and construction. Journal of Construction Engineering and Management, 136(7), 730-744.

Ellis, G. (2020). Sensing the Future of Building: The Role of Sensors in Construction. Autodesk Construction Cloud. Retrieved from: https://constructionblog.autodesk.com/sensors-in-construction/

ElHassouni, J., El-Qadi, A., Bazzi, M., and El Haziti, M. (2020). Modeling with ontologies design patterns: credit scorecard as a case study. Indonesian Journal of Electrical Engineering and Computer Science, 17(1), 429-439.

Ergen, E., & Akinci, B. (2007, September). An overview of approaches for utilizing RFID in construction industry. In 2007 1st Annual RFID Eurasia (pp. 1-5). IEEE. Retrieved from: https://ieeexplore.ieee.org/abstract/document/4368087

Esser, D., Schuster, D., Muthmann, K., & Schill, A. (2014, April). Few-exemplar Information Extraction for Business Documents. In ICEIS (1) (pp. 293-298). Retrieved from: https://www.scitepress.org/papers/2014/49467/49467.pdf

Fagin, R., Kimelfeld, B., Reiss, F., & Vansummeren, S. (2016). A relational framework for information extraction. ACM SIGMOD Record, 44(4), 5-16. Retrieved from: https://dl.acm.org/doi/pdf/10.1145/2935694.2935696?casa_token=H2zubrpSVpMAAAAA:F3xnEDY26HBnOJYtq8Zyvh_o7aFFqXfEr6zVJi4Ya_pPwtroHT4ImmenvR65fKLuo1jU2-3eyLncmQ

Falotico, R., & Quatto, P. (2015). Fleiss' kappa statistic without paradoxes. Quality & Quantity, 49(2), 463-470. Retrieved from: https://search.proquest.com/docview/1653049799?fromopenview=true&pq-origsite=gscholar

Fan, R., Wang, L., Yan, J., Song, W., Zhu, Y., & Chen, X. (2020). Deep Learning-Based Named Entity Recognition and Knowledge Graph Construction for Geological Hazards. ISPRS International Journal of Geo-Information, 9(1), 15. Retrieved from: https://www.mdpi.com/2220-9964/9/1/15

Fang, W., Love, P. E., Luo, H., & Ding, L. (2020). Computer vision for behaviour-based safety in construction: A review and future directions. Advanced Engineering Informatics, 43, 100980. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1474034619305531?casa_token=a36RLHiwj_AAAAAA:s0r8CG2SZ66-9Vye9SPeJwRQhihZwSG-kccL3JIJ0SABYrC54ScBFamyxHSivvlkQm4l8DfdMg

Fautsch, C., & Savoy, J. (2009). Algorithmic stemmers or morphological analysis? An evaluation. Journal of the American Society for Information Science and Technology, 60(8), 1616-1624. Retrieved from: https://asistdl.onlinelibrary.wiley.com/doi/full/10.1002/asi.21093?casa_token=aFpDvpMqcZ8AAAAA%3A-0HPnjdJevYlq_NqakZ1O9D-rBFk5-CyxjnMewNDw55oPxu9l0g586qjUFIcrCjvFBcvngG--NZlBzb_

Fleming, W. S. (2016). BIM modelling for structural analysis. Poznan University of Technology. Retrieved from: https://www.semanticscholar.org/paper/BIM-modelling-for-structural-analysis-Fleming/75ea167797a918bdefeaa2706a001b94e15b7db5

Framework, I. (2004). EUROPEAN INTEROPERABILITY FRAMEWORK FOR PAN-EUROPEAN eGOVERNMENT SERVICES. Retrieved from: https://elfarchive1718.foi.hr/pluginfile.php/55018/mod_resource/content/1/EIF.pdf

Fu, F. (2015). Advanced modelling techniques in structural design. John Wiley & Sons. Retrieved from: https://www.researchgate.net/profile/Feng-Fu-6/publication/276309004_Advanced_Modelling_Techniques_in_Structural_Design/links/5dbdeb274585151435e2641d/Advanced-Modelling-Techniques-in-Structural-Design.pdf

Gennari, J. H., Musen, M. A., Fergerson, R. W., Grosso, W. E., Crubézy, M., Eriksson, H., ... and Tu, S. W. (2003). The evolution of Protégé: an environment for knowledge-based systems development. International Journal of Human-computer studies, 58(1), 89-123.

Guarino, N., Oberle, D., and Staab, S. (2009). What is an ontology?. In Handbook on ontologies (pp. 1-17). Springer, Berlin, Heidelberg. DOI 10.1007/978-3-540-92673-3

Guo, X., Tian, C., Chen, Y., and Zhang, J. (2021). "Case Study of Building Information Modeling Implementation in Infrastructure Projects." J. Transportation Research Record, 00(0), 1-17

Gourlis, G., & Kovacic, I. (2017). Building Information Modelling for analysis of energy efficient industrial buildings–A case study. Renewable and Sustainable Energy Reviews, 68, 953-963. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1364032116002173?casa_token=uzlLjWQ7m8IAAAAA:FVgcvb-T1efxkkJxWJJ0gotK6PASFdC3ihqxOeCqXalrRezpVz3VmUtOwUg895XrN0wIEl_nHQ

Goutte, C., & Gaussier, E. (2005, March). A probabilistic interpretation of precision, recall and F-score, with implication for evaluation. In European conference on information retrieval (pp. 345-359). Springer, Berlin, Heidelberg. Retrieved from: https://link.springer.com/chapter/10.1007/978-3-540-31865-1_25

Grilo, A., & Jardim-Goncalves, R. (2010). Value proposition on interoperability of BIM and collaborative working environments. Automation in construction, 19(5), 522-530. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580509001733?casa_token=dK_FD9OZMdcAAAAA:0Pb0iNSBrwY-2ADhFkzZWbM2vt-kEiS2DaqRREJKKdmM7ozt0uOTO-7SDWeBGqpXLuSA9JHK5A

Grishman, R., & Sundheim, B. M. (1996). Message understanding conference-6: A brief history. In COLING 1996 Volume 1: The 16th International Conference on Computational Linguistics. Retrieved from: https://www.aclweb.org/anthology/C96-1079.pdf.

Harris, C. M. (2006). Dictionary of Architecture and Construction. McGraw-Hill.

Hietanen, J., & Final, S. (2006). IFC model view definition format. International Alliance for Interoperability, 1-29. Retrieved from: https://library.ahima.org/doc?oid=60942#.YEguBmhKgoM

Hlomani, H., & Stacey, D. (2014). Approaches, methods, metrics, measures, and subjectivity in ontology evaluation: A survey. Semantic Web Journal, na (na), 1-5.

Howell, I., & Batcheler, B. (2005). Building information modeling two years later–huge potential, some success and several limitations. The Laiserin Letter, 22(4), 3521-3528. Retrieved from: http://www.laiserin.com/features/bim/newforma_bim.pdf

Hu, Z. Z., Zhang, X. Y., Wang, H. W., & Kassem, M. (2016). Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. Automation in Construction, 66, 29-42. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580516300152?casa_token=Qn0jIl-BlxUAAAAA:N25B9dbn9mYVr4Aq2clXt1ouNOlS1JsfA5jTPlbd_SRsUvKYlQ-aqtiichR5jxHQRf_hhLFGnw

Ibrahim, A., & Golparvar-Fard, M. (2019). 4D BIM based optimal flight planning for construction monitoring applications using camera-equipped UAVs. In Computing in Civil Engineering 2019: Data, Sensing, and Analytics (pp. 217-224). Reston, VA: American Society of Civil Engineers. Retrieved from: https://ascelibrary.org/doi/abs/10.1061/9780784482438.028

IGI Global (2021). IGI Global Dictionary. Retrieved from: https://www.igi-global.com/dictionary/building-information-modeling-australian-architecture/1428

Isikdag, U., Underwood, J., & Aouad, G. (2008). An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes. Advanced engineering informatics, 22(4), 504-519. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1474034608000499?casa_token=OKZsdIXqMzEAAAAA:gJvFIDF01Qa09sJ4VWgaReZyt79YttTprZE8qW4RXS3lA1yN_2lxTzA2KRAWat-LRUavnnX8_Q

Kamel, E., & Memari, A. M. (2019). Review of BIM's application in energy simulation: Tools, issues, and solutions. Automation in construction, 97, 164-180. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580517304958?casa_token=xDvVk7YUar8AAAAA:ZRT8F1aTfMxUGQ0fEBirREPF7h2LtD8mzK_UwjYvhC3qkYoK4sDdJ2Gi6x1uKkVeVf_CrRFSrw

Kalny, O. (2013). “CSI knowledge base.” <https://wiki.csiamerica.com/display/etabs/Home > (Aug. 28, 2017).

Khan, L., and Luo, F. (2002). Ontology construction for information selection. In 14th IEEE International Conference on Tools with Artificial Intelligence, 2002.(ICTAI 2002). Proceedings. (pp. 122-127). IEEE. DOI: 10.1109/TAI.2002.1180796

Kim, H., Ham, Y., Kim, W., Park, S., & Kim, H. (2019). Vision-based nonintrusive context documentation for earthmoving productivity simulation. Automation in Construction, 102, 135-147. Retrieved from: https://www.sciencedirect.com/science/article/pii/S092658051830671X?casa_token=vxGX8w0AvtkAAAAA:WPUTcAWWe0NWlI3FZwTEFzr3NsbHWRFhCBH8cfdLzssleYCpFxUU8tvYvRnikGbqbfGxfQDrUQ

Kiviniemi, A. (2008). “IFC certification process and data exchange process.” in: A. Zarli, R. Scherer (Eds.), ECCPM 2008, Taylor & Francis Group, Sophia Antipolis, France, 2008, p. 8.

Kübler, S., McDonald, R., & Nivre, J. (2009). Dependency parsing. Synthesis lectures on human language technologies, 1(1), 1-127. Retrieved from: https://www.morganclaypool.com/doi/pdfplus/10.2200/S00169ED1V01Y200901HLT002?casa_token=Y9_XGqO_WvUAAAAA%3ApRoEw0aVC9DIaMcDtLFDtFuAzEmpz60vcCL6yulYwTNXMeJ1S0EhO85dSF9J_OL3uUgUgdyMD5M&

Laakso, M., & Kiviniemi, A. O. (2012). The IFC standard: A review of history, development, and standardization, information technology. ITcon, 17(9), 134-161. Retrieved from: http://usir.salford.ac.uk/id/eprint/28373/1/History_of_IFC_standard.pdf

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. biometrics, 159-174. Retrieved from: https://www.jstor.org/stable/pdf/2529310.pdf?casa_token=CIJevCYERIUAAAAA:f37CKN6JFOGCIpghnl66kUP9H6NyGA3KZY62hIzOQ9cww9H-qTR75xuDR754G5H3NaLU327GxTV-PGy6HMh5Q3DZ-pwhy33yv0ecm1ToDny3u0Fn0FJU

Larsen, J. K., Shen, G. Q., Lindhard, S. M., & Brunoe, T. D. (2016). Factors affecting schedule delay, cost overrun, and quality level in public construction projects. Journal of Management in Engineering, 32(1), 04015032. Retrieved from: https://ascelibrary.org/doi/full/10.1061/%28ASCE%29ME.1943-5479.0000391?casa_token=6zol9Qf9c9YAAAAA%3APVFPQZix9EuqqZ0M_bVmjCYApQd76NYBmloUKgAHR48co5B97rH6oh_myxkQAV9wtV3RuDH0rj8J

Lee, Y.C., Ghannad, P., Dimyadi, J., Lee, J.K., Solihin, W., and Zhang, J. (2020). "A comparative analysis of five rule-based model checking platforms." Proc., ASCE Construction Research Congress, ASCE, Reston, VA, 1127-1136.

Lee, P. C., Wang, Y., Lo, T. P., & Long, D. (2018). An integrated system framework of building information modelling and geographical information system for utility tunnel maintenance management. Tunnelling and Underground Space Technology, 79, 263-273. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0886779818300312?casa_token=65fQFK8TWhwAAAAA:9ngAIU5vOg-hCaaAqFt5XyWRkNyWrjRExuenFwjwubAcuVMTEZM4T9k7zod0Y19dO7e_TfajDA

Li, H., and Zhang, J. (2021). "Interoperability between BIM and BEM using IFC." Proc., 2021 ASCE International Conference on Computing in Civil Engineering, ASCE, Reston, VA.

Li, Q., Zhang, H., and Zhang, L. (2018). Application of Building Information Modeling (BIM) Technology in Information Management of Steel Structure Materials. In ICCREM 2018: Innovative Technology and Intelligent Construction (pp. 278-284). Reston, VA: American Society of Civil Engineers. Retrieved from: https://ascelibrary.org/doi/abs/10.1061/9780784481721.033

Liebich, T. (2013, March). IFC4—The new buildingSMART standard. In IC Meeting. Helsinki, Finland: bSI Publications. Retrieved from: http://standards.buildingsmart.org/IFC/RELEASE/IFC4/buildingSMART_IFC4_What-is-new.pdf

Liu, Y., Van Nederveen, S., & Hertogh, M. (2017). Understanding effects of BIM on collaborative design and construction: An empirical study in China. International journal of project management, 35(4), 686-698. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0263786316300461?casa_token=nVoAiCexBtIAAAAA:IfCFm5lYiOhzdIRdHlTo5Uq_D-3ZOkMekAT14hh0NqUBmetn0gtp2oOMWFp2WVIMJI7MLqaj2w

Liu, Z. Q., and Zhang, J. (2015). “BIM-based structural analysis model and data conversion application.” *Industrial Construction*, 45(2), 4-5.

Lines, B. C., Sullivan, K. T., Smithwick, J. B., & Mischung, J. (2015). Overcoming resistance to change in engineering and construction: Change management factors for owner organizations. International Journal of Project Management, 33(5), 1170-1179. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0263786315000095?casa_token=EjMaDUGEXawAAAAA:_8TwykF5-tm6o_HWEqTnYbTt2KTRoLMwHHoaXssPL4LBnXox_NBlmQ-yH6Bc-Sf1wloluOgqyQ

Ma, Z., and Liu, S. (2018). “A review of 3D reconstruction techniques in civil engineering and their applications.” Advanced Engr. Informatics, 37, 163-174.

Manning, C., & Schutze, H. (1999). Foundations of statistical natural language processing. MIT press. Retrieved from: https://books.google.com/books?hl=en&lr=&id=3qnuDwAAQBAJ&oi=fnd&pg=PT12&dq=Foundations+of+statistical+natural+language+processing&ots=ysG0r4BtJW&sig=RPsATrlRJgxyyOXGzYxg-FCKtII#v=onepage&q=Foundations%20of%20statistical%20natural%20language%20processing&f=false

McGuinness, D. L., and Van Harmelen, F. (2004). OWL web ontology language overview. W3C recommendation, 10(10), 2004.

Motik B., Glimm. B., Stoilos. G., Horrocks. I., and Shearer. R. (2021). HermiT. Protégé. Retrieved from: https://protegewiki.stanford.edu/wiki/HermiT.

Moens, M. F. (2006). Information extraction: algorithms and prospects in a retrieval context (Vol. 21). Springer Science & Business Media. Retrieved from: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.396.2533&rep=rep1&type=pdf

Mujumdar, P., & Maheswari, J. U. (2018). Design iteration in construction projects–Review and directions. Alexandria Engineering Journal, 57(1), 321-329. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1110016816303210

Muller, M. F., Garbers, A., Esmanioto, F., Huber, N., Loures, E. R., & Canciglieri, O. (2017). Data interoperability assessment though IFC for BIM in structural design–a five-year gap analysis. Journal of Civil engineering and management, 23(7), 943-954. Retrieved from: https://www.tandfonline.com/doi/abs/10.3846/13923730.2017.1341850

Nawari, N. (2011). Standardization of structural BIM. In Computing in Civil Engineering (2011) (pp. 405-412). Retrieved from: https://ascelibrary.org/doi/abs/10.1061/41182(416)50

Nojedehi, P., O'brien, W., and Gunay, H. B. (2021). Benchmarking and visualization of building portfolios by applying text analytics to maintenance work order logs. Science and Technology for the Built Environment, 1-25. DOI: 10.1080/23744731.2021.1913957

Noy, N. F., and McGuinness, D. L. (2001). Ontology development 101: A guide to creating your first ontology.

Oliphant, T. E. (2007). Python for scientific computing. Computing in Science & Engineering, 9(3), 10-20. Retrieved from: https://ieeexplore.ieee.org/document/4160250

Omar, T., & Nehdi, M. L. (2016). Data acquisition technologies for construction progress tracking. Automation in Construction, 70, 143-155. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580516301376?casa_token=lgFVHBLlCscAAAAA:bREi1EcBsbBBCQOcMr2XBkugvUAyM-9ryolGBS3Xd1K9ceD9s1xdk6t7-n_iRzKwVN9vABsHtA

Oraee, M., Hosseini, M. R., Papadonikolaki, E., Palliyaguru, R., & Arashpour, M. (2017). Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. International Journal of Project Management, 35(7), 1288-1301. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0263786317300790?casa_token=rIpFmFjIyvUAAAAA:caLiIA5F9Ff87tYyxvUfA7eH4DDgB9jnHZAoXsr-4s90Hs_GSZK4h8rm6M7CaWyLiODdu7n7rA

Park, C. S., Lee, D. Y., Kwon, O. S., & Wang, X. (2013). A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. Automation in construction, 33, 61-71. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580512001598?casa_token=8WKROw5SAjwAAAAA:Eiuv9wmEF6kuVBXWT35A4CZFIk0Fl3xKfhr_LMiA5zOwPv6txls9zCChYyLw24vP9eXbX8Jxzw

Penabad, A. J. C. (2018). Picking up where we left off the typological diagram as a fundamental tool for a conscious architectural design process. Journal of Geography, 6(1), 11-18. Retrieved from: http://jgesnet.com/journals/jges/Vol_6_No_1_June_2018/2.pdf

PGT. (2020). Retrieved from: https://www.arcat.com/sdspecs/htm04/08_15_00pgt.htm

Piñeres-Espitia, G., Cama-Pinto, A., DE LA ROSA, D., Estevez, F., & Cama-Pinto, D. (2017). Design of a low cost weather station for detecting environmental changes. Revista Espacios, 38(59). Retrieved from: https://www.revistaespacios.com/a17v38n59/17385913.html

Poku, S. E., & Arditi, D. (2006). Construction scheduling and progress control using geographical information systems. Journal of computing in civil engineering, 20(5), 351-360. Retrieved from: https://ascelibrary.org/doi/pdf/10.1061/(ASCE)0887-3801(2006)20%3A5(351)?casa_token=0ho9WseCW9IAAAAA:I5ONhgrWoVr7RXQ2x01X3v3gLsZAp_WKtrs_aUTz2gjd-n6-F-HZYz9tOpamW5U5ZLuGxc7O30K-

Ramaji, I. J., & Memari, A. M. (2018). Interpretation of structural analytical models from the coordination view in building information models. Automation in Construction, 90, 117-133. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580518301286?casa_token=j4Xe5lN86xgAAAAA:qEi-ypX80NeF1UG4atZrNuZvyO3A0g0e8KlEEUqyKxVYC-zjSQ15wRWFfAoo1jBcquZx2DIB8Q

Raad, J., and Cruz, C. (2015). A survey on ontology evaluation methods. In Proceedings of the International Conference on Knowledge Engineering and Ontology Development, part of the 7th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management.

Ren, Z., Anumba, C. J., & Tah, J. H. M. T. (2011). RFID-facilitated construction materials management (RFID-CMM)–A case study of water-supply project. Advanced Engineering Informatics, 25(2), 198-207. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1474034610000042?casa_token=Hy1iJcmraqkAAAAA:SbFL0TbNNrUwZCDWbFRMFBWiK4cpLj5a-W2astAKSRA-oCAYM-3eVAw4mRw35b7z9Ez-pcEt2A

Ren, R., Zhang, J., & Dib, H. N. (2018). BIM interoperability for structural analysis. In Construction Research Congress 2018: Construction Information Technology. Retrieved from: https://par.nsf.gov/servlets/purl/10058656

Ren, R., & Zhang, J. (2019). Model information checking to support interoperable bim usage in structural analysis. In Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation (pp. 361-368). Reston, VA: American Society of Civil Engineers. Retrieved from: https://par.nsf.gov/servlets/purl/10104661

Ren, R., & Zhang, J. (2021a). A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions. Advances in Civil Engineering, 2021.

Ren, R., & Zhang, J. (2021b). Semantic Rule-Based Construction Procedural Information Extraction to Guide Jobsite Sensing and Monitoring. Journal of Computing in Civil Engineering, 35(6), 04021026.

Ren, R., Zhang, J., & Tang, P (2021a). An Ontology-Based Interface to Guide Jobsite Sensing and Construction Tasks/Applications to Support Construction Information Management. In Preparation

Roh, S., Aziz, Z., & Peña-Mora, F. (2011). An object-based 3D walk-through model for interior construction progress monitoring. Automation in Construction, 20(1), 66-75. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580510001019?casa_token=e30xEuarR_kAAAAA:irgmTy-iZ3ymhoLAAr7vkWRaaFhCDBWQNpReqZvmg15ZUfbF9z9Iaw0FCnuuJU6A7EA-VyZe6A

Ren, R., Zhang, J., & Jiang, Y. (2021b). New Automated Activity-on-Node Calculation Grading Method for Construction Management Education Innovation. Journal of Civil Engineering Education, 147(3), 04021004.

Ren, R., Zhang, J., & Chen, Y. (2020). An automated grading method for activity-on-node calculations to support construction management education. In Construction Research Congress 2020: Safety, Workforce, and Education (pp. 733-742). Reston, VA: American Society of Civil Engineers.

Sacks, R., Kaner, I., Eastman, C. M., & Jeong, Y. S. (2010). The Rosewood experiment—Building information modeling and interoperability for architectural precast facades. Automation in construction, 19(4), 419-432. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580509001824?casa_token=-tMpKN3y67gAAAAA:t6R5oi3dL_5MAmhLdZ6_rtDCXXCtVqrbps4I0RlNzNKz2WN5NMaPy4kEqjCB3mKXi2Js9NHsOg

Safa, M., Baeza, S., and Weeks, K. (2019). Incorporating Blockchain technology in construction management. Strategic Direction. https://doi.org/10.1108/SD-03-2019-0062

Sanguinetti, P., Abdelmohsen, S., Lee, J., Lee, J., Sheward, H., & Eastman, C. (2012). General system architecture for BIM: An integrated approach for design and analysis. Advanced Engineering Informatics, 26(2), 317-333. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1474034611001108?casa_token=bteMdmZIIH4AAAAA:rqKJiTbKIsz7t_JM6PjBrD8QtTqRFyplisyDki1vXfvpuakJCW3JWztAzZwRffI04_CwP82Ugg

Serrano-Juan, A., Pujades, E., Vázquez-Suñè, E., Crosetto, M., & Cuevas-González, M. (2017). Leveling vs. InSAR in urban underground construction monitoring: Pros and cons. Case of la sagrera railway station (Barcelona, Spain). Engineering Geology, 218, 1-11. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0013795216308675?casa_token=g1fYzF3i8sMAAAAA:TMuXhDhVBipciUYyY83_kYHO7-b0Q3On-ECR-N18a0BksQPlrX_zDAQS6up4UQLAiJ4dXJw7TA

Sherafat, B., Ahn, C. R., Akhavian, R., Behzadan, A. H., Golparvar-Fard, M., Kim, H., ... & Azar, E. R. (2020). Automated methods for activity recognition of construction workers and equipment: state-of-the-art review. Journal of Construction Engineering and Management, 146(6), 03120002. Retrieved from: https://ascelibrary.org/doi/full/10.1061/(ASCE)CO.1943-7862.0001843?casa_token=oAkKtnZQ6FAAAAAA:PVvWMd2BJRtR442e-xWv_8AJUkv8uL90q7oLeNJA4930Y0Ak-B07KGV-WHFIKouyCU_h6MduxI0i

Sheng, D., Ding, L., Zhong, B., Love, P. E., Luo, H., & Chen, J. (2020). Construction quality information management with blockchains. Automation in Construction, 120, 103373. https://doi.org/10.1016/j.autcon.2020.103373

Shi, L., Zhang, Y., Cheng, J., & Lu, H. (2019). Two-stream adaptive graph convolutional networks for skeleton-based action recognition. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (pp. 12026-12035). Retrieved from: https://openaccess.thecvf.com/content_CVPR_2019/papers/Shi_Two-Stream_Adaptive_Graph_Convolutional_Networks_for_Skeleton-Based_Action_Recognition_CVPR_2019_paper.pdf

Shin, T. S. (2017). Building information modeling (BIM) collaboration from the structural engineering perspective. International Journal of Steel Structures, 17(1), 205-214. Retrieved from: https://link.springer.com/content/pdf/10.1007/s13296-016-0190-9.pdf

Shirowzhan, S., Sepasgozar, S. M., Edwards, D. J., Li, H., & Wang, C. (2020). BIM compatibility and its differentiation with interoperability challenges as an innovation factor. Automation in Construction, 112, 103086. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580519309215?casa_token=D02M5npVxZ0AAAAA:InmVURl3pqT0g6jTshtIQe9O2GiCpoZaNoY7S-XZQT2YTaqQD6BlYYG7WfvQyNVCieiXZdoaqA

Shults, R., Levin, E., Habibi, R., Shenoy, S., Honcheruk, O., Hart, T., and An, Z. (2019). CAPABILITY OF MATTERPORT 3D CAMERA FOR INDUSTRIAL ARCHAEOLOGY SITES INVENTORY. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences. https://doi.org/10.5194/isprs-archives-XLII-2-W11-1059-2019

Smith, B. (2003). Ontology. Luciano Floridi (ed.), Blackwell Guide to the Philosophy of Computing and Information. Oxford: Blackwell. pp. 155-166 (2003), Retrieved from: https://philpapers.org/archive/SMIO-11

Singh, S. (2018). Natural language processing for information extraction. arXiv preprint arXiv:1807.02383. Retrieved from: https://arxiv.org/pdf/1807.02383.pdf.

Solnosky, R. L., Memari, A. M., & Ramaji, I. J. (2014, February). Structural BIM processes for modular multi-story buildings in design and construction. In 2nd residential building design & construction conference (pp. 201-215). Retrieved from: https://www.researchgate.net/profile/Issa-J-Ramaji/publication/272092243_Structural_BIM_Processes_for_Modular_Multi-story_Buildings_in_Design_and_Construction/links/54da99ff0cf2ba88a68d4d0d/Structural-BIM-Processes-for-Modular-Multi-story-Buildings-in-Design-and-Construction.pdf

Steel, J., Drogemuller, R., & Toth, B. (2012). Model interoperability in building information modelling. Software & Systems Modeling, 11(1), 99-109. Retrieved from: https://eprints.qut.edu.au/37725/1/c37725a.pdf

Su, C. (2007). Analyzing Management Processes Within a Distributed Team Context: The Case of a Canada-China Construction Project (Doctoral dissertation, École polytechnique). Retrieved from: https://central.bac-lac.gc.ca/.item?id=MR36942&op=pdf&app=Library&oclc_number=429725329

Sukkarieh, J. Z., & Pulman, S. G. (2005, May). Information extraction and machine learning: Auto-marking short free text responses to science questions. In Proceedings of the 2005 conference on artificial intelligence in education: Supporting learning through intelligent and socially informed technology (pp. 629-637). Retrieved from: https://dl.acm.org/doi/abs/10.5555/1562524.1562609

Sun, J., Lei, K., Cao, L., Zhong, B., Wei, Y., Li, J., and Yang, Z. (2020). Text visualization for construction document information management. Automation in Construction, 111, 103048. https://doi.org/10.1016/j.autcon.2019.103048

Sweets. (2020). Retrieved from: https://sweets.construction.com/BrowseByDivision

Thuraisingham, B. (2004). Secure sensor information management and mining. IEEE Signal Processing Magazine, 21(3), 14-19. DOI: 10.1109/MSP.2004.1296538.

Teizer, J. (2008). 3D range imaging camera sensing for active safety in construction. Journal of Information Technology in Construction (ITcon), 13(8), 103-117. Retrieved from: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.211.9668&rep=rep1&type=pdf

Tian, Y., Yang, X., & Arditi, A. (2010, July). Computer vision-based door detection for accessibility of unfamiliar environments to blind persons. In International Conference on Computers for Handicapped Persons (pp. 263-270). Springer, Berlin, Heidelberg. Retrieved from: https://d1wqtxts1xzle7.cloudfront.net/41367160/Computer_Vision-Based_Door_Detection_for20160121-28992-evxpjw.pdf?1453378487=&response-content-disposition=inline%3B+filename%3DComputer_Vision_Based_Door_Detection_for.pdf&Expires=1615778215&Signature=TQej46Y8Y44jZN1UIojXC9wftlAm0qk4YsnT3TiIhtmAnYLjFqY02hm~2Jb7IIomWOgP9ttj~j6TcDszrk80jhyrLOdRadclJ8rT7T4VLPev7cW1HniGgRM4vFz~cllnaFTFfCkooz0lMHVEPzwRoGY7YAThbT5L3P82W4MgiPAapgxsIp2o~Voxn6KMWUihptjQHasCJ3lGg1qFfKnzv1XvUu7rB3jISI3HuHOUkz1~JjFBbjJIGnhx74O~N4WcXyRzpLM1SN5wNKiWj7sFh8DIP3EGC~Jgn6zKaqtRJsql--ALkClYR6EQ2QYjtBOFCeOpcV0b8VOWpQ52dLkL6g__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

Ülkeryıldız, E. (2015). A model for evaluating the absorptive capacity of architectural design teams. Retrieved from: https://openaccess.iyte.edu.tr/xmlui/handle/11147/4459

Ulanov, A., Shevlyakov, G., Lyubomishchenko, N., Mehra, P., & Polutin, V. (2010). Monte Carlo Study of Taxonomy Evaluation. In Database and Expert Systems Applications (DEXA), 2010 Workshop on (pp. 164-168). IEEE.

Vähä, P., Heikkilä, T., Kilpeläinen, P., Järviluoma, M., and Gambao, E. (2013). Extending automation of building construction—Survey on potential sensor technologies and robotic applications. Automation in construction, 36, 168-178. DOI: https://doi.org/10.1016/j.autcon.2013.08.002

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. Automation in construction, 38, 109-127. Retrieved from: https://www.sciencedirect.com/science/article/pii/S092658051300191X?casa_token=GxfagwQktbYAAAAA:GLtASuA0Qg5M1ZafM7oMKb-fld_pRgdb0NvFK-5BMB76qoVx_YwKJx5hm9QnUYvx9tvN3ao_aw

Wan, C., Chen, P., and Tiong, R. L. K. (2004). "Assessment of IFCs for structural analysis domain." *J., Information Technology in Construction*, 9 (2004), 75-75,88-88.

Wang, X., Kim, M. J., Love, P. E., & Kang, S. C. (2013). Augmented Reality in built environment: Classification and implications for future research. Automation in construction, 32, 1-13. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580512002166?casa_token=E2PTD2A6KHkAAAAA:YlEAloIpTLkBzqHWNnrg-v7eqjpZS6ZpJISHRAbdA4UQW0RmvEgyKv57-buOK_oivp1-eaZLCg

Wang, Y., Tang, P., Liu, K., Cai, J., Ren, R., Lin, J.J., Cai, H., Zhang, J., El-Gohary, N., Berges, M., and Golparvar-Fard, M. (2022). “Characterizing data sharing in civil infrastructure engineering: Current practice, future vision, barriers, and promotion strategies.” J. Comput. in Civ. Eng., under review.

Watson, A. (2011). Digital buildings–Challenges and opportunities. Advanced engineering informatics, 25(4), 573-581. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1474034611000516?casa_token=ypIVs8XFkLYAAAAA:mRaR7MwgZYZv_Ehs9CKrZ7eojKHVPXCx-Fs2nzNDK75FKZ_jw0zrsdTSZi48oGfQuofcvs62BQ

Wiley, V., & Lucas, T. (2018). Computer vision and image processing: a paper review. International Journal of Artificial Intelligence Research, 2(1), 29-36. Retrieved from: http://ijair.id/index.php/ijair/article/view/42/0

Wong Chong, O., and Zhang, J. (2021). "Logic Representation and Reasoning for Automated BIM Analysis to Support Automation in Offsite Construction." Journal of Automation in Construction, 129(September 2021), 103756

Wong Chong, O., & Zhang, J. (2019). Game Simulation to Support Construction Automation in Modular Construction Using BIM and Robotics Technology—Stage I. In Computing in Civil Engineering 2019: Data, Sensing, and Analytics (pp. 376-383). Reston, VA: American Society of Civil Engineers. Retrieved from: https://par.nsf.gov/servlets/purl/10104672

Wu, J., Sadraddin, H. L., Ren, R., Zhang, J., & Shao, X. (2021). Invariant signatures of architecture, engineering, and construction objects to support BIM interoperability between architectural design and structural analysis. Journal of Construction Engineering and Management, 147(1), 04020148.

Wu, J., and Zhang, J. (2019). “New automated BIM object classification method to support BIM interoperability.” J. Comput. Civ. Eng., 33(5), 04019033.

Xu, X., and Cai, H. (2021). Domain Ontology for Utility Infrastructure: Coupling the Semantics of CityGML Utility Network ADE and Domain Glossaries. Journal of Computing in Civil Engineering, 35(5), 04021011.

Xu, J., Shi, Y., Xie, Y., and Zhao, S. (2019). A BIM-Based construction and demolition waste information management system for greenhouse gas quantification and reduction. Journal of Cleaner Production, 229, 308-324. https://doi.org/10.1016/j.jclepro.2019.04.158

Xue, X., Wu, J., and Zhang, J. (2022). “Semi-Automated Generation of Logic Rules for Tabular Information in Building Codes to Support Automated Code Compliance Checking.” Journal of Computing in Civil Engineering, 36(1), 04021033.

Xue, X., Zhang, J., and El-Gohary, N. (2022). “Interactive visual representation of inter-connected requirements in building codes.” Proc., ASCE Construction Research Congress, ASCE, Reston, VA.

Xue, X., and Zhang, J. (2021). “Part-of-speech tagging of building codes empowered by deep learning and transformational rules.” J. Adv. Eng. Inform., 47(January 2021), 101235.

Xue, X., and Zhang, J. (2020). “Building codes Part-of-Speech tagging performance improvement by error-driven transformational rules.” J. Comput. in Civ. Eng., 34(5), 04020035.

Yalcinkaya, M., & Singh, V. (2014, July). Building information modeling (BIM) for facilities management–literature review and future needs. In IFIP International Conference on Product Lifecycle Management (pp. 1-10). Springer, Berlin, Heidelberg. Retrieved from: https://link.springer.com/content/pdf/10.1007/978-3-662-45937-9_1.pdf

Yan, X., Li, H., Li, A. R., & Zhang, H. (2017). Wearable IMU-based real-time motion warning system for construction workers' musculoskeletal disorders prevention. Automation in Construction, 74, 2-11. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580516303314?casa_token=OzQ2grSZ4O0AAAAA:8qNM8XR2UYoU0xc-wuha3i88D_EAAmgCRMjKOaYlhDle8e-zN_UOQX4y7KUuiVqEhIn42FyVWQ

Yang, C. H., Pang, Y., & Soergel, U. (2017). Monitoring of building construction by 4D change detection using multi-temporal SAR images. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 4, 35. Retrieved from: https://d-nb.info/1143871871/34

Yang, L. N., Zhou, Z. F., & Zhu, L. J. (2009). Ceramic substrate's detection system based on machine vision. In 4th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Optical Test and Measurement Technology and Equipment (Vol. 7283, p. 72834I). International Society for Optics and Photonics. Retrieved from: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/7283/72834I/Ceramic-substrates-detection-system-based-on-machine-vision/10.1117/12.828828.short?SSO=1

Yang, Q. Z., & Zhang, Y. (2006). Semantic interoperability in building design: Methods and tools. Computer-Aided Design, 38(10), 1099-1112. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0010448506001011?casa_token=IvbnhrhmmkwAAAAA:pX0_uouzsH1msx9HnMcVX9hUN5xQ4FOMbVB72F03fRhiQw3CcbtnhlgYk1jJHJ524wHMxTgKPQ

Yin, J., Yang, Q., and Pan, J. J. (2008). Sensor-based abnormal human-activity detection. IEEE Transactions on Knowledge and Data Engineering, 20(8), 1082-1090. DOI: 10.1109/TKDE.2007.1042.

Yu, X., Han, Z., Gong, Y., Jan, N., Zhao, J., Ye, Q., ... & Shi, H. (2020). The 1st Tiny Object Detection Challenge: Methods and Results. arXiv preprint arXiv:2009.07506. Retrieved from: https://arxiv.org/pdf/2009.07506.pdf

Zeng, X., Lu, X., and Xu, Z. (2014). “Modeling technology for building aseismic elasto-plastic analysis based on BIM data.” *Computer Aided Engineering,* 23(4), 3-3.

Baker, C.A., Rapp, R.R., Elwakil, E., and Zhang, J. (2019). “Infrastructure assessment post-disaster: Remotely sensing bridge structural damage by unmanned aerial vehicle in low-light conditions.” J. Emerg. Manag., 18(1), 27-41.

Zhang, J., and Laddipeerla, S. (2018). "A feasibility study of IFC-based BIM 4D simulation using commercial systems to support construction planning in the U.S." Proc., 54th ASC Annual International Conference, ASC, Fort Collins, CO, 441-448.

Zhang, J., & El-Gohary, N. M. (2016). Semantic NLP-based information extraction from construction regulatory documents for automated compliance checking. Journal of Computing in Civil Engineering, 30(2), 04015014. Retrieved from: https://ascelibrary.org/doi/pdf/10.1061/(ASCE)CP.1943-5487.0000346?casa_token=WCbzmtvH4VgAAAAA:GLYxgevGecbIe5ojgU1jj_neNzzah_hAX9RWAs3ir9-OLPruPc8uED4hTqWS1r8y4VDgTz63X2fb

Zhang, J., and El-Gohary, N. (2015). "Automated extraction of information from building information models into a semantic logic-based representation." Proc., 2015 ASCE Intl. Workshop on Comput. in Civ. Eng., ASCE, Reston, VA, 173-180.

Zhang, J., and El-Gohary, N. (2013). "Semantic NLP-based information extraction from construction regulatory documents for automated compliance checking." J. Comput. in Civ. Eng., 30(2), (Invited), 04015014.

Zhang, J., and El-Gohary, N. (2012). "Automated regulatory information extraction from building codes leveraging syntactic and semantic information." Proc., ASCE Construction Research Congress, ASCE, Reston, VA, 622-632.

Zhong, B., Xing, X., Luo, H., Zhou, Q., Li, H., Rose, T., & Fang, W. (2020). Deep learning-based extraction of construction procedural constraints from construction regulations. Advanced Engineering Informatics, 43, 101003. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1474034619305762?casa_token=Fz3d2hJp4ScAAAAA:ehrZR8YzAkbi7ZOCTF0afdKhAJH1Nb9tl-oJTIajv7WYj9hJZ7_59IQBg5oN_lwT-4zqmgWIhg

Zhou, P., & El-Gohary, N. (2017). Ontology-based automated information extraction from building energy conservation codes. Automation in Construction, 74, 103-117. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0926580516302230?casa_token=h5QpSVUpv_8AAAAA:dJk6NdxYa1mbll5mzD01tJuXy2sl4xFEuqFw6bMYbk64VwnxJln2SdH-h-iwoOjeVsCveCqxPA

Ziegler, S., Woodward, R. C., Iu, H. H. C., & Borle, L. J. (2009). Current sensing techniques: A review. IEEE Sensors Journal, 9(4), 354-376. Retrieved from: https://ieeexplore.ieee.org/document/4797906

PUBLICATIONS

Ren, R., Zhang, J., and Dib, H. N. (2018). BIM interoperability for structural analysis. In Construction Research Congress 2018: Construction Information Technology. : https://ascelibrary.org/doi/abs/10.1061/9780784481264.046

Ren, R., and Zhang, J. (2019). Model information checking to support interoperable BIM usage in structural analysis. In Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation (pp. 361-368). Reston, VA: American Society of Civil Engineers. : https://doi.org/10.1061/9780784482421.046

Ren, R., and Zhang, J. (2020). Comparison of BIM interoperability applications at different structural analysis stages. In Construction Research Congress 2020: Computer Applications (pp. 537-545). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784482865.057

Ren, R., Zhang, J., and Chen, Y. (2020). An automated grading method for activity-on-node calculations to support construction management education. In Construction Research Congress 2020: Safety, Workforce, and Education (pp. 733-742). Reston, VA: American Society of Civil Engineers.

Ren, R., and Zhang, J. (2021). "An integrated framework to support construction monitoring automation using natural language processing and sensing technologies." Proc., 2021 ASCE International Conference on Computing in Civil Engineering, in press.

Ren, R., Zhang, J., and Jiang, Y. (2021). New Automated Activity-on-Node Calculation Grading Method for Construction Management Education Innovation. Journal of Civil Engineering Education, 147(3), 04021004.

Ren, R., and Zhang, J. (2021). A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions. Advances in Civil Engineering, 2021. https://doi.org/10.1155/2021/8824613

Ren, R., and Zhang, J. (2021). Semantic Rule-Based Construction Procedural Information Extraction to Guide Jobsite Sensing and Monitoring. Journal of Computing in Civil Engineering, 35(6), 04021026. DOI: 10.1061/(ASCE)CP.1943-5487.0000971.

Ren, R., Shatnawi, A. M., Shao, X., Zhang, J., Wu, J., and Sadraddin, H.L. (2021). Enhancing Interoperable BIM Applications with Invariant Signatures of AEC Objects - A Case Study on Structural Analysis of a High-Rise Building Model. (In Preparation)

Ren, R., Zhang, J., Chen, Y., and Dib, H.N. (2022). "A BIM information processing framework to facilitate enriched BIM applications." Proc., ASCE Construction Research Congress, ASCE, Reston, VA, accepted.

APPENDIX A: MATERIAL REUSE PERMISSION FROM PUBLISHERS

J

Jane Rose Rose Mercado <help@hindawi.com>
Tue 10/5/2021 1:42 AM
To: Ran Ren

Dear Dr. Ren,

Thank you for your patience.

Articles published in Hindawi's journals are made freely available on our website. They are distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

You can download the full-text PDF by clicking on the link in the right-hand menu on the side of the article page. Additionally, if you go to the home page of any of our published articles, you will see a small menu in the top right corner of the page that includes a heading titled "Download Citation." Click on this link to display the correct format for citation.

If I can be of further assistance, please do not hesitate to contact me.

Best regards,

Jane Rose

Jane Rose Mercado
Support Specialist

Hindawi.com | Twitter | FaceBook | LinkedIn | YouTube

P

PERMISSIONS <permissions@asce.org>
Fri 10/15/2021 1:25 PM
To: ASCE Library <ascelibrary@asce.org>; Ran Ren

Dear Ran,

Thank you for your inquiry. As an original author of an ASCE journal article or proceedings paper, you are permitted to reuse your own content (including figures and tables) for another ASCE or non-ASCE publication (including dissertation), provided it **does not account for more than 25% of the new work**.

A full credit line must be added to the material being reprinted. For reuse in non-ASCE publications, add the words "With permission from ASCE" to your source citation. For Intranet posting, add the following additional notice: "This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers.

Each license is unique, covering only the terms and conditions specified in it. Even if you have obtained a license for certain ASCE copyrighted content, you will need to obtain another license if you plan to reuse that content outside the terms of the existing license. For example: If you already have a license to reuse a figure in a journal, you still need a new license to use the same figure in a magazine. You need a separate license for each edition.

For more information on how an author may reuse their own material, please view: http://ascelibrary.org/page/informationforasceauthorsreusingyourownmaterial

Sincerely,
Nadine Canavan
Publications Sales & Marketing
Sales Coordinator
American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, VA 20191

PERMISSIONS@asce.org

703-295-6080
Internet: www.asce.org/pubs | www.ascelibrary.org | http://ascelibrary.org/page/rightsrequests

APPENDIX B: IMPLEMENTATION FIELDS OF INFORMATION CHECKING AND INFORMAITON EXTRACTION FOR CHAPTER 5

```python
import ifcopenshell
import re
ifc_file = ifcopenshell.open("journal.ifc")
extendedproperties = ifc_file.by_type("IfcExtendedMaterialProperties")
extendedproperty = extendedproperties[0]
if extendedproperty in ifc_file:
    print('[Data]', extendedproperty)
else:
    print('[Info]', "IfcExtendedMaterialProperties doesn't exist")


materialselects = ifc_file.by_type("IfcMaterialSelect")
materialselect = materialselects[:]
if materialselect in ifc_file:
    print('[Data]', materialselect)
else:
    print('[Info]',"IfcMaterialSelect doesn't exist")


materials = ifc_file.by_type("IfcMaterial")
material = materials[0]
print('[Data]', material)
##singlevalue = ifc_file.by_type ("IfcPropertySingleValue")
##singlevalue = singlevalue [0]
##print (singlevalue. Name)


singlevalue = ifc_file.by_type("IfcPropertySingleValue")
ifcconversionbasedunit = ifc_file.by_type("IfcConversionBasedUnit")
PROPERTIES = ['CompressiveStrength', 'MassDensity', 'PoissonRatio', 'ShearModulus', 'ThermalExpansionCoefficient', 'YoungModulus']

for n in range(0,6):
    if PROPERTIES[n] in str(singlevalue):
        #print("STRENGTH FCU", PROPERTIES[n]);
        print('[Info]', PROPERTIES[n], "exis")
    else:
        compressivestrength = float(input("Please input CompressiveStrength of the material (Unit:Psi): "));
        unit_compressivestrength=input("Please input unit of CompressiveStrength of the material: ");
        print("STRENGTH FCU", compressivestrength * 145.038 / 10E6);
for item in singlevalue:
    if 'CompressiveStrength' in item:
        print('[Data]', item)
        print('[Info]', item.Name)
        y = str(item.NominalValue)
        print('[Info]', re.findall(x,y))
        print('[Info]', item.Unit)
    elif "MassDensity" in item:
        print('[Data]', item)
        print('[Info]', item.Name)
        print('[Info]', item.NominalValue)
        print('[Info]', item.Unit)
    elif "PoissonRatio" in item:
        print('[Data]', item)
        print('[Info]', item.Name)
        print('[Info]', item.NominalValue)
        print('[Info]', item.Unit)
    elif "ShearModulus" in item:
        print('[Data]', item)
        print('[Info]', item.Name)
        print('[Info]', item.NominalValue)
        print('[Info]', item.Unit)
    elif "ThermalExpansionCoefficient" in item:
        print('[Data]', item)
        print('[Info]', item.Name)
        print('[Info]', item.NominalValue)
        print('[Info]', item.Unit)
    elif "YoungModulus" in item:
        print('[Data]', item)
        print('[Info]', item.Name)
        print('[Info]', item.NominalValue)
        print('[Info]', item.Unit)
```