Design and the Built Environment

Developing BIM-enabled Work Packaging with Field Sensing for Information Flow Improvement in Complex Projects

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

Under the agreement on the dual Ph.D. degree program between Curtin University and National Taiwan University, this thesis contains no material which has been accepted for the award of any other degree of diploma in any university.

Signature: ………………………………………………

Date: 19th July, 2021

Statement of Author's Contributions

To Whom It May Concern

I, Yuan-Hao Tsai, contributed abstract, introduction, related research studies, the framework, system design and implementation, conclusions, limitations, future works, and references significantly to the publication entitled "A BIM-based approach for predicting corrosion under insulation" .

Yuan-Hao Tsai

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I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

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Prof. Shang-Hsien Hsieh

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ABSTRACT

The amount of information in a project can increase significantly due to innovative designs, increasing adoption of emerging technologies, and complicated management processes. Although this information can be made available to all project stakeholders, when decision-making occurs, some information is neglected or not considered. The omitted information is essentially a wasted resource, which does not add value to the project. An effective management of information flow is the key to reducing wasted information, yet it accounts for the largest proportion of issues during a project lifecycle. The primary goal in this research is to develop an innovative data environment to reduce the potential wasted resources so as to improve the information flow in projects.

This research develops an integrated common data environment (CDE) to accommodate the project information from multiple sources. In the proposed common data environment, the BIM-based field sensing approach is developed to monitor site conditions which serves for the information demands when decision making. Besides, the BIM-enabled work packaging approach is developed to organise the information from various disciplines and working schedules. A series of work packages could be layouted to specify the tasks, and the linkages are automatically generated afterwards on the basis of the properties inside. Therefore, the field sensing information and work packages are well-organised and cross-referenced in the proposed CDE. It provides relevant information as much as possible when decision making occurs which is considered to be versatile and capable of reducing information waste. In consequence, the improvement of information flow in complex projects is achieved.

Theoretical and practical implications of this research are provided for stakeholders along with the project lifecycle. It provides a continuous information flow to stream site conditions from site to office and interpret the sensor data in useful information to support the decision making. Besides, project information from multiple stakeholders is organised and linkages among project information are automatically generated which provides a novel approach to arrange and analyse multiple sources of project information. The versatility of the common data environment shows an insight of integrating multiple emerging technologies to suffice various demands of information.

Keywords: building information model, common data environment, work packaging, smart sensing technology, information management

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LIST OF ABBREVIATIONS

3D	Three-Dimensional
4D	Four-Dimensional
AEC	Architecture, Engineering, and Construction
API	Application Programming Interface
AR	Augmented Reality
AWP	Advanced Work Packaging
AWS	Amazon Web Service
BIM	Building Information Modelling
BPMN	Business Process Modelling Notation
CDE	Common Data Environment
CR	Corrosion Rate
CRUD	Create, Read, Update, and Delete
CWP	Construction Work Package
EDP	Element-Data Pair
EWP	Engineering Work Package
HTTP	Hypertext Transfer Protocol
IaaS	Infrastructure as a Service
IC	Integrated Circuit
IoT	Internet of Things
ISO	International Organization for Standardization
IT	Information Technology
IWP	Installation Work Package
LiDAR	Light Detection and Ranging
LOD	Level of Detail
LPS	Last Planner System
NoSQL	Not Only Structured Query Language

PaaS	Platform as a Service
PPC	Planned Percent Complete
PWP	Procurement Work Package
RESTful API	Representational State Transfer Application Programming Interface
RFID	Radio Frequency Identification
RFI	Request for Information
ROI	Return of Investment
SaaS	Software as a Service
UHF	Ultra-High Frequency
VR	Virtual Reality
WBS	Work Breakdown Structure
WSN	Wireless Sensor Network

Chapter 1: Introduction

1.1 Background

The amount of information in a project can increase significantly due to innovative designs, increasing adoption of emerging technologies, and complicated management processes. Although this information can be made available to all project stakeholders, the information is poorly distributed to the right person at the right time. Specifically, as stakeholders perform project work at different times throughout the project lifecycle, they each might have their own way of organising information. Additionally, there may be a lack of an explicit and versatile information structure to accommodate various types of information. As a result, when decision-making occurs, some information is neglected or not considered. The omitted information is essentially a wasted resource, which does not add value to the project. To address these issues, the mechanism of how information is collected, organised, and captured for making decisions needs to be redesigned.

Smart sensing technologies could be utilised to collect site data and then integrate them into a building information modelling (BIM) system. The integrated information could be further interpreted to meaningful information which is beneficial for understanding site conditions. The analysed results could be visualised on BIM models to facilitate decision making as well. As to organising multiple sources of information throughout the project lifecycle, a work packaging approach with spatial information from BIM models could be designed to strengthen connections among project data. Geometric information from BIM models and non-geometric data from work packages can be properly interconnected throughout a thoughtful mechanism. Afterwards, the linkages among project information could reduce the potential information waste during the decision making process because related information is extracted as much as possible. To apply the aforementioned applications throughout the project lifecycle, a common data environment (CDE) needs to be established to accommodate all sources of data. An integrated framework should be designed to combine the advantages of collecting field information and organising project information.

1.2 Problem Statement

Information flow is a theoretical concept describing the information transfer from information sources to adopters among stakeholders throughout the project lifecycle (Eckert et al., 2001). Ideally, the information should reach the right stakeholders at the right time to form an effective information flow (Rathnasinghe et al., 2020). A smooth information flow is especially important during construction as there is a constant need for communication between project manager, contractors, subcontractors, and foremen (Tauriainen & Leväniemi, 2020). Therefore, understanding the formation of information flow is crucial in order to streamline the information flow.

Generally, the contractual role of each stakeholder could determine how the information is shared or how stakeholders interact with the received deliverables. These determinations could lead to different paths of information flow. Alternatively, deliverables could influence the information flow by their information structure due to the different processes of collecting and using the information (Froese, 2010; A. Phelps & Horman, 2008). Ultimately, the decisions of stakeholders and deliverables build a basic information flow of a project.

To elaborate the information flow in detail, Figure 1 exemplifies various contractual roles from different stakeholders throughout the project lifecycle. Specifically, the project manager normally receives information from owners or clients about their idea and expected outcomes, and gets the possible designs or solutions from consultants and engineering teams. The project manager then integrates this information and passes it to the construction company. After receiving the design information, the construction manager who is in charge of the project distributes the works to several superintendents and monitors the progress and budget. Each superintendent then arranges the works and passes each task to corresponding subcontractors. Material and equipment suppliers may be contacted to suffice the needs on site during the construction as well. Meanwhile, the subcontractors assign foremen to lead the workers to accomplish specific tasks on site. In short, the aforementioned example indicates that each stakeholder follows their contractual role in the project which naturally forms the information flow throughout the project lifecycle.

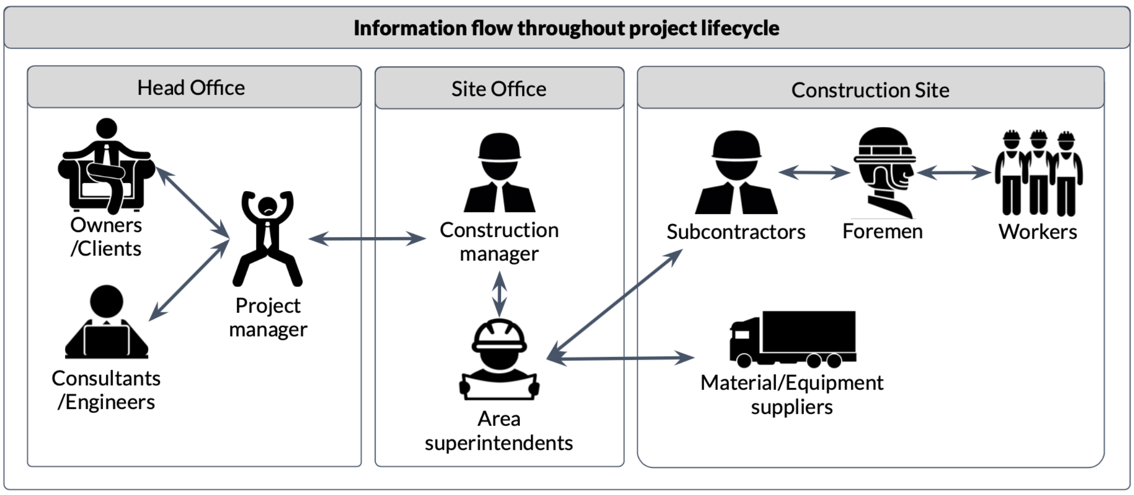


Figure 1. Stakeholders' contractual role in the project

While an information flow facilitates the sharing of information within a project, it nevertheless does not guarantee a proper use of information in a project. In fact, the interactions among stakeholders and deliverables determine whether the information is accepted, rejected, or ignored (Andreas F. Phelps & Reddy, 2009). If a piece of information is accepted, it is adopted in a decision that could add value to the project. However, if it is rejected or ignored, it may be discarded and eventually disappear from the project. An analysis of information flow in an integrated project delivery (IPD) project aligns with the statements that excess information flow increases effectiveness only until the stakeholders suffer from information overload (Hickethier et al., 2013; Kratzer et al., 2008). The stakeholders may cut some information flows to balance their capacity which increases the possibility of missing information. Therefore, effective management of information flows is necessary for maximizing the value of a project (Hartman & Ashrafi, 2002; Andreas F. Phelps & Reddy, 2009).

This phenomenon is illustrated in Figure 2 (A. F. Phelps, 2012). Both new and existing information are added as inputs to the data pool. These inputs could be collective memory which is the knowledge or experience from stakeholders, parameters set by past decisions, previously captured information in boundary objects which could be drawings, reports, BIM models, or request for information (RFI) sheets. These data may refer to each other and then be captured in collective memory, decisions, or boundary objects when needed. As stakeholders with different backgrounds and at varying times add data, the data pool might seem like a black box. This situation indicates that if the data is not captured in collective memory, decisions, or boundary objects, they will be deemed as a waste.

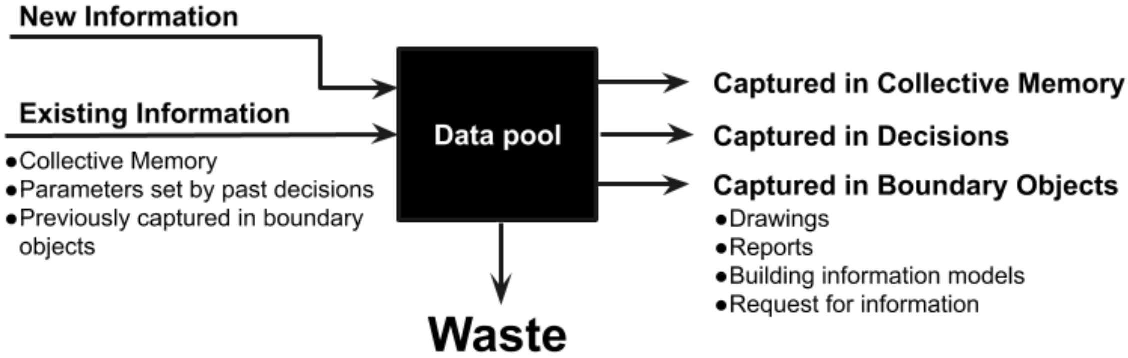


Figure 2. Information flow in a project

An effective management of information flow is the key to reducing wasted information, yet it is one of the top human-related issues in project information management. An ineffective management of information flow is an issue during the project lifecycle (Chan et al., 2004). According to Bryde et al. (Bryde et al., 2013), the reciprocal interdependencies among stakeholders is one of the complexities in information management (Figure 3). Specifically, these stakeholders, such as authorities, designers, engineers, contractors, and suppliers, typically participate in a project at different times, leading to a difficulty in passing or exchanging information (Koskinen, 2004). Furthermore, stakeholders with different backgrounds all work with each other, which is characteristic of a construction project. As a result, the data pool in such a project may be complex and it may be challenging to extract necessary information, especially when there is a lack of consistent methods for information flow throughout the project lifecycle.

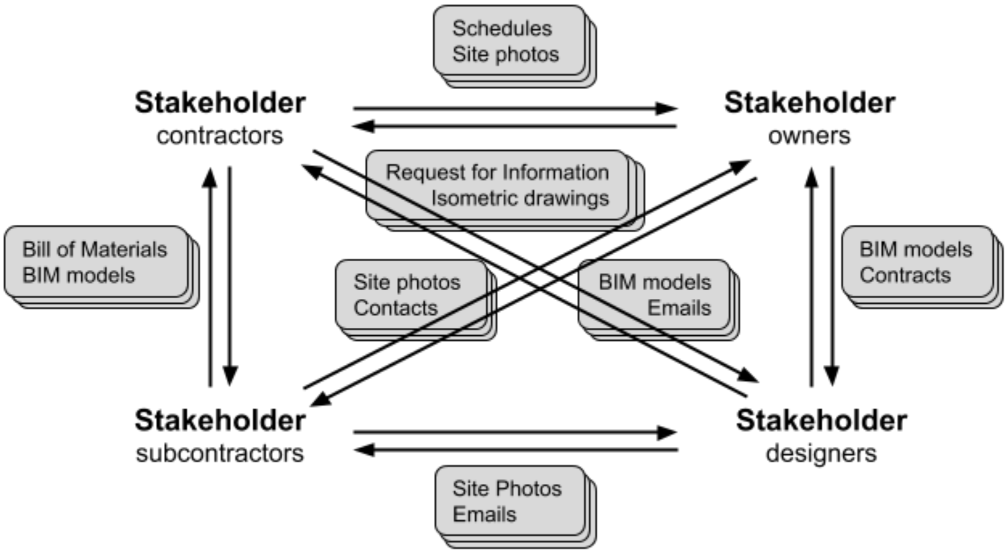


Figure 3. The interdependencies of stakeholders

1.3 Research Aim and Objectives

To tackle the problem from Section 1.2, this research aims to develop an innovative data environment to improve the information flow in complex projects. The data environment leverages the smart sensing technology and BIM to receive interpreted site information, and organises project information through a BIM-enabled work packaging approach to strengthen the linkages among project information. To achieve this aim, three objectives are established in the sequential order of information flow as follows:

Objective 1: Monitoring site conditions with BIM and field sensing information for decision making in complex projects.

A field sensing framework for leveraging smart sensing technology and BIM will be developed to interpret sensor data to meaningful information. Because of the continuous information from the site, it benefits the decision making process by providing sufficient information of site conditions. Within the framework, the hardware layout of smart sensing will be identified and the capability test of the sensors will be conducted.

Besides, the mechanism of interpretation will be proposed. An application will be developed to demonstrate the feasibility of the framework.

Objective 2: Designing BIM-enabled work packaging for strengthening information linkages in complex projects.

A BIM-enabled work packaging approach will be designed to link geometric and non-geometric data in the project. Specifically, spatial information from the BIM model is paired to most of the project data. The paired data then serves as the essential pieces of the work package which describes each task in the project lifecycle. Throughout the work packaging process proposed in the approach, the tasks in the project could be organised in a logical manner that complies with construction practice. Additionally, work packages from all stakeholders could be automatically linked together based on the dedicated schema of work packages. Therefore, beyond detailing tasks with geometric and non-geometric data, this approach also outlines the relationship of the tasks in the project.

Objective 3: Integrating field sensing information and BIM-enabled work packaging for improving information flow in complex projects.

A CDE-supported framework will be proposed to accommodate multiple sources of information generated from Objective 1 and 2. Because of the information integration feature of the proposed framework, the project information could be adapted at the maximum degree to support the decision making process throughout the project lifecycle. To validate the potential of the proposed framework, two pilot studies will be conducted. The first pilot study will demonstrate the integrity of project information by planning details of construction inspection before the site trip. By preparing most of the inspection tasks in the office, spot checks will mainly involve data collection on site which simplifies the information management of the inspection process. The second pilot study will demonstrate the enhanced linkages among the project information. A change impact scenario will be shown and related work packages will be identified. The information flow could be improved by reducing the wasted information along with the decision making process.

1.4 Significance and Contribution of the Research

Project communication management involves different levels of planning and managing procedures to ensure the information needs of a project are met (Gillard & Johansen, 2004; Project Management Institute, 2017). However, the essential characteristics of projects in the architecture, engineering, and construction (AEC) industry such as numerous stakeholders and various disciplines challenge the communications (Atkinson, 1999). As the number of complex projects grows, more and more projects confront communication problems in the global construction market (Loosemore & Muslmani, 1999). To effectively manage increasing amounts of information from innovative design, technologies, and procedures across stakeholders, effective communication throughout the project lifecycle is essential (Clarke, 1999; Loosemore & Muslmani, 1999). The research targeting to improve information flow throughout the project lifecycle has a profound effect on how information is received, organised, and exchanged for each stakeholder. Three objectives derived from the aim of the research are established in Section 1.3. The contribution of each objective elaborates as follows:

To start with, the proposed field sensing framework (*Objective 1*) provides a novel approach for acquiring site information to make decision making progress. Sensor data are interpreted to site information which precisely and continuously reflects the condition on site. Decision makers are benefited from a better understanding of site conditions which leads to a less wasted information of a project.

Next, a BIM-enabled work packaging mechanism (*Objective 2*) strengthens the information linkages in the project lifecycle. Data from multiple stakeholders could be organised by a consistent method and cross-referenced to each other. The well-organised project data serves the information needs from stakeholders by offering relative project data as much as possible. This reduces the wasted information along with the information flow.

Lastly, a CDE-supported framework (*Objective 3*) leveraging approaches from objective 1 and 2 to streamline information among multiple stakeholders along with the project lifecycle. Specifically, the framework retains the field sensing capability from objective 1 and the cross-referenced information from objective 2. Furthermore, because the framework follows the principles of CDE which is designed for collaboration between project members, the versatility of the framework fits various demands in project management. Consequently, the framework leads to an improved information flow with less information waste along the project lifecycle.

1.5 Structure of the Thesis

This thesis is composed of seven chapters, as shown in Figure 4, illustrating as the followings:

Chapter 1 is an introduction that provides the background of the research. Then, the problem statement concludes the issues to be improved in the background. Research aim and derived objectives are established accordingly. Significance and contributions of the research are highlighted as well.

Chapter 2 presents the literature review in the field of sensing technology, relationships of project information in the project lifecycle, and the principles and standards of common data environments regarding the information management perspective. These reviews correspond to the three objectives listed in Chapter 1.

Chapter 3 describes the research design implemented in this research. There are three sections corresponding to the three objectives: (1) Research design for developing BIM-enabled site monitoring for decision making; (2) Research design for developing BIM-enabled work packaging for information linkages; and (3) Research design for designing common data environments for project information management.

Chapter 4 proposes a framework for leveraging BIM and field sensing to interpret site data into useful information for decision making. An experimental testbed is selected to demonstrate and verify the feasibility of the framework.

Chapter 5 develops a framework for strengthening information linkages among project information. An experiment is conducted to verify the effectiveness of the proposed approach.

Chapter 6 proposes a common data environment to integrate multiple sources of project information and two pilot studies are performed to illustrate the versatility of the proposed common data environment.

Chapter 7 concludes the research findings and then explains the theoretical contributions and practical implications. Recommendations for future research are also highlighted.

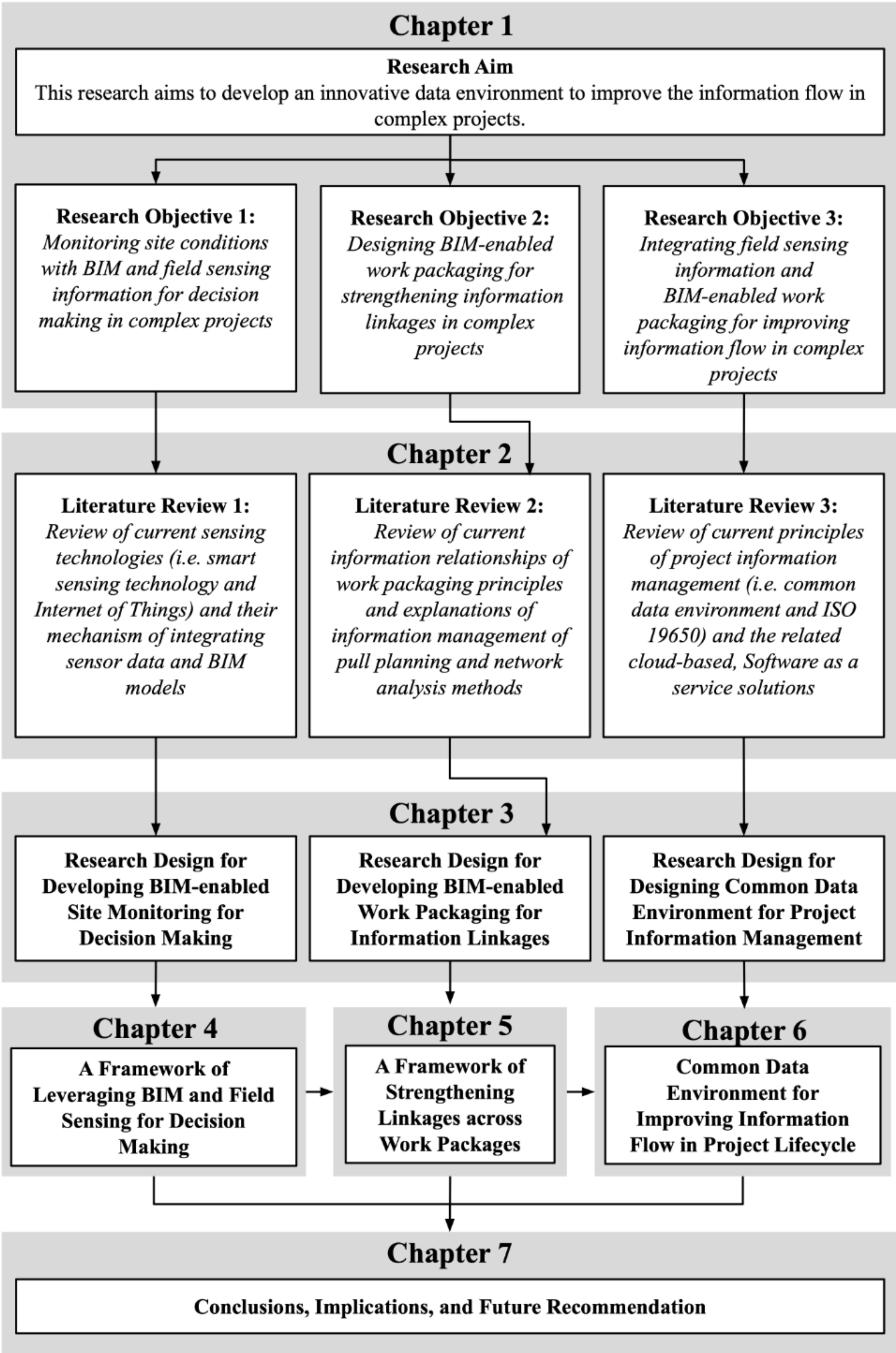


Figure 4. Structure of the dissertation

Chapter 2: Literature Review

2.1 Site Monitoring with BIM

In this section, technologies for monitoring site conditions are reviewed. The strategies of selecting sensors, the mechanism of the information exchange, and the visualisation of sensing information are reviewed to summarise the potential of supporting decision making process with site monitoring data.

2.1.1 Smart Sensing Technologies

Sensors are devices that detect the physical environment and convert the measurements to electrical signals (Fraden, 2016). Typically, sensors contain only the sensor itself and outsource the signal processing and communication work. System integrators thus have full access to the sensor in the process which is beneficial for sensor calibration in a particular environment. Regarding the power and size, sensors vary from type to type because of the different systems they hosted on. Therefore, sensors provide an underlying structure for integrators to customise each component of the sensing system. On the other hand, smart sensors are sensors with a microprocessor and wireless communication module embedded in the integrated circuit (IC) (Frank, 2013). With the processing and communication capabilities, smart sensors are capable of processing raw data on sensors and then sharing the calibrated values to the system. System integrators generally access the converted sensor values instead of electric signals from sensors. In terms of power source, smart sensors contain the module to generate or store power. The power from the module is low and limits the capability of data processing. Nevertheless, the module makes smart sensors self-sustaining which lowers the barriers for system integration. Additionally, because all necessary components for sensing are integrated into smart sensors, the size of smart sensors are mostly small and can be adopted in a wide variety of environments. In short, Table 1 summarises the features of sensors and smart sensors to compare the differences.

Table 1. Comparison of sensors and smart sensors

Features	**Sensors**	**Smart Sensors**
Processor	No embedded processor	Embedded microprocessor
Sensor data conversion	Need external compute resources to convert raw data	Processing data conversion onboard
Communication	Wired, one-way communication	Wireless, two-way communication
Sensor control	Full access	Converted sensor values
Power	Various power consumption according to types of sensors	Low power consumption
Size	Various sizes according to types of sensors	Mostly small

Generally, both sensors and smart sensors can measure the environment, proximity, vision, or motion in the physical world (Table 2). System integrators may adopt sensors or smart sensors based on the aforementioned features to suit the sensing scenarios. In particular, environment sensors detect the temperature, humidity, sound, or gas in the space. An energy analysis experiment was conducted to measure the environment in a demonstration house (Kuo et al., 2016). Sensors are chosen instead of smart sensors because there is no demand for a compact design of sensing system. On the contrary, for the safety monitoring or facility management on sites, a real-time, wireless, compact sensing system is prefered (W.-F. Cheung et al., 2018; Riaz et al., 2017; Yuan Hao Tsai et al., 2019). Smart sensors are selected to monitor the temperature, humidity, and gas. The sensing data then is sent to the system wirelessly for management strategy.

For the proximity measurement, technologies including ultrasonic, laser, bluetooth, or camera could be utilised. The determination of technologies is a technical decision according to the environment because the sensor may be placed in the water, or sealed in a metallic shell which needs dedicated technologies for proximity measurement. For example, a robotic tool was built to inspect concrete surfaces in tunnels (Victores et al., 2011). The laser technology which is suitable in a tunnel environment was integrated into the proximity sensor mounted on a wheeled vehicle. Besides, smart proximity sensors based on bluetooth technology were integrated for indoor positioning (Park et al., 2017). The smart proximity sensors are installed across the site to detect the distance between target devices and sensors. The position then can be calculated which cultivates the safety monitoring on site.

Regarding the vision sensors, various technologies including light detection and ranging (LiDAR), color, light, infrared and camera can be adopted. However, some technologies such as LiDAR and cameras normally need high computing power to convert the raw data into useful information. The technologies are more applicable on sensors instead of smart sensors because they rely on external power sources. For example, cameras are installed on the tower crane to serve the navigation system for blind lifting (G. Lee et al., 2012). LiDAR was implemented to monitor the construction progress on site (Abbas et al., 2020; Jun Wang et al., 2015). To adopt smart sensors for vision monitoring, light technology which has low power consumption was implemented to monitor the traffic for better traffic control (Klepa et al., 2019).

Lastly, the motion monitoring could be realised by accelerometer, pressure, or gyroscopes sensing. The selection could be attributed to the sensing scenario. For example, accelerometers are selected to monitor the vibration in the railway tunnel (Lai et al., 2015). The vibration sensors were installed in each segment of the tunnel and formed a vibration sensing array. It helps monitor the structural health of tunnels. On the other hand, the smart sensors with accelerometers and gyroscopes were selected to monitor the posture of construction workers (Valero et al., 2017). Because of the small size and lower power design, the smart sensors could be placed in the wearable devices for construction workers. The devices then assess the inadequate working posture to protect the workers' health.

In conclusion, various categories of sensing technologies could be adopted. Table 2 summarises the categories of the sensors and smart sensors. Use cases are listed according to each category. It shows that sensors and smart sensors have their own merits in the scenarios.

Table 2. Categories of sensors and smart sensors

Categories	**Sensors**	**Smart Sensors**
Environment (temperature, humidity, sound, gas…)	Energy analysis (Kuo et al., 2016)	Construction safety (W.-F. Cheung et al., 2018; Riaz et al., 2017) Facility management (Yuan Hao Tsai et al., 2019)
Proximity (ultrasonic, laser, bluetooth, camera...)	Tunnel inspection (Victores et al., 2011)	Indoor positioning for safety monitoring (Park et al., 2017)
Vision (LiDAR, color, light, infrared, camera…)	Site lifting (G. Lee et al., 2012) Quality control (Abbas et al., 2020; Jun Wang et al., 2015)	Traffic control (Klepa et al., 2019)
Motion	Vibration monitoring (Lai et	Worker posture (Valero et al.,

(accelerometer, pressure, gyroscopes…)	al., 2015)	2017)

Smart sensing technology has been implemented on pipeline monitoring in the industry due to its main features: little processor, small size, wireless, and low-cost (Dener & Bostancıoğlu, 2015; Spencer et al., 2004). Specifically, smart sensors are able to collect data on site and send the data back to stations wirelessly with the low installation and maintenance cost (Aalsalem et al., 2018). In terms of the communication mechanisms, Wireless Sensor Network (WSN) and Radio Frequency Identification (RFID) are the two common systems used in smart sensing (Ruiz-Garcia et al., 2009). WSN consists of several sensor nodes which can use Bluetooth, Wi-Fi, or ZigBee to communicate. On the other hand, RFID systems are formed of active or passive RFID tags and RFID readers (Arulogun et al., 2016). Because of different demands of monitoring on sites, these systems have been implemented in the industry in different scenarios (Petersen et al., 2007; Yuan Hao Tsai et al., 2019). In short, smart sensing technology is a reliable method and widely used in industry to steam data from site to office.

There are various types of smart sensing technologies that can be implemented on site. In addition, many of them are integrated to BIM models across the building lifecycle. For example, regarding site management during construction, customised sensors are designed and installed in confined spaces to monitor work site and process data. The sensor values are streamed to servers and integrated into BIM models as well. When health and safety hazards happen, the health and safety department could take necessary actions with adequate information (Riaz et al., 2014). During construction, video sensors and laser sensors are adopted and integrated with BIM technology to provide an easy-to-use and useful navigation system for tower crane operators. Instead of numerical data from collision-detection systems, tower crane operators could understand surroundings in three-dimensional (3D) environments better. It is proved by on site implementation that tower crane operators heavily rely on the proposed navigation system compared with the numerical anti-collision system (G. Lee et al., 2012). The integration of sensing and BIM technologies could be implemented in the operation and maintenance stage as well. Series of sensors are installed on the bridge deck deicing system to monitor the state of the bridge deck under different climate conditions (J. Chen et al., n.d.). In brief, integration of sensing and BIM technologies could be implemented across lifecycle for both buildings and infrastructures.

One of the commonly used sensors on site is RFID sensors. Ordinarily, there are two types of RFID sensors, passive and active. Both passive and active RFID sensors can receive signals from readers, and return the encoded information. However, the mechanism of the sensors is different. Passive RFID sensors generate power from the reader's signal which means they do not need batteries. Therefore, they can last for a long period. On the other hand, active RFID sensors have batteries. They send out signals powered by themselves. Because of the difference of power source, an active RFID sensor usually provides a longer read range than a passive RFID sensor; however, the lifetime of an active RFID sensor is generally shorter than a passive RFID sensor. Several research studies are conducted to leverage RFID sensors for information integration. A pilot study from Meadati et al. (Meadati et al., 2010) points out that RFID sensors could reduce tedious works of mapping digital objects to elements in the real world. In the following research, an integration of RFID sensors and BIM models is implemented to simulate the lighting levels on a physical model in real-time which helps testing the facade system before construction (Kensek, 2014). To sum up, the aforementioned research utilised sensing and BIM technologies to build the bridge between digital environment and real site. This connection could be adopted in this research to collect site conditions for the decision making processes.

2.1.2 Internet of Things (IoT)

IoT is the concept of embedding physical objects (things) with sensors to exchange data with others over the internet. Namely, sensing devices are able to interconnect and share information in a unified platform (C. Z. Li et al., 2018). It accelerates the progress of digital transformation in the AEC industry by providing environmental or location data for operational management (Teizer et al., 2017). This versatility makes IoT applicable across the entire building lifecycle. Besides, by integrating BIM and IoT, research studies point out that abundant information in BIM models and real-time data from IoT devices formulate a powerful paradigm to improve construction and operational efficiencies (Arthur et al., 2018; Zhai et al., 2019).

Considering the applications of IoT technology, construction operation and monitoring, health and safety management, construction logistic management, and facility management are the main focuses of the research studies. Among these domains, the construction operation and monitoring accounts for the largest proportion (Mohammed et al., 2020; S. Tang et al., 2019). It shows that implementing IoT in the construction stage is the current trend, and the approaches from these studies provide insights for designing interfaces for stakeholders to explore the integrated information. For instance, the platform called Otaniemi3D integrates the built environment data with IoT sensors to provide energy usage, occupancy, and user comfort of the buildings on campus (Dave et al., 2018). The proposed framework and the system architecture clarify the advantages and limitations of integrating IoT and BIM technologies. Another study shows that the prefabricated construction benefits from the IoT-enabled BIM platform. The platform collects data from RFID sensors to achieve real-time visibility and traceability of the processes (Zhong et al., 2017). It shows the potential of how the real-time captured data facilitates the processes of making advance decisions by stakeholders. In short, research studies show that IoT is beneficial for connecting and sharing the real-time sensor data which suffices the information needs of a timely decision making process. By integrating the IoT with BIM, multiple sources of information can further be interconnected and this provides a real-time interface for stakeholders to manipulate project information.

2.1.3 Sensing Data Integration

BIM has been largely implemented for information integration throughout the building lifecycle (Salman Azhar et al., 2012; Eadie et al., 2013; Ham et al., 2008). Approaches, frameworks, systems, and platforms are therefore proposed to meet the different needs. Generally, the applications could be categorised into planning, construction, maintenance stages (Table 3). In the planning stage, feasibility of the design could be analysed such as cost, safety assessment, and sustainability analysis through the 3D integrated platform powered by BIM (Campisi et al., 2020; Carvalho et al., 2021; F. K. T. Cheung et al., 2012; Solla et al., 2019). These research studies validate that project information can be leveraged by BIM to review the design in an holistic view in the early phase. Regarding design applications, BIM technology integrates multiple sources of information and visualises the data in a 3D environment (Röck et al., 2018). It improves the quality of stakeholders' engagements as well as the design review processes (Donato et al., 2018). The integration facilitates the decision making process and has been confirmed that the return of investment (ROI) in BIM is worthwhile (Giel, Brittany K. & Issa, Raja R. A., 2013). Besides, the design is normally analysed in the planning stage to optimise the energy consumption or structural strength of the building (Salman Azhar & Brown, 2009; F. Tang et al., 2020). By utilising the BIM models as the information repositories, inputs of algorithms for optimisation can be retrieved and updated without idle time.

In the construction stage, BIM technology can be implemented into abundant applications including the top concerns on site such as schedule, quality, cost, and human resource. In terms of the schedule, research studies show that the BIM technology facilitates progress monitoring (Rebolj et al., 2017), automatic scheduling (ElMenshawy & Marzouk, 2021; Z. Wang & Azar, 2019), and mitigating the risk of delay (C. Z. Li et al., 2017). Because of the three dimensional capability of BIM, both time and space can be considered when scheduling which ensures the timely project delivery. Also, the quality management during the construction can be enhanced. An indoor positioning system integrated with BIM technology was proposed for quality control on site (Ma et al., 2018). Because of the abundant data binding to BIM models, quality information can not only be accessed but also located by the proposed system which reduces the possible omissions from workers along the process. Besides, a lot of research studies proposed novel approaches leveraging the latest technologies to perform the inspection. For example, AR technology was adopted to inspect the structural elements on site (Mirshokraei et al., 2019). Drones were sent to the site to collect the real-time site information and then integrated into a BIM-AR platform (Liu et al., 2021). The video frames of site information can be automatically matched to the BIM model which speeds up the inspection process in large project sites. LiDAR technology was implemented to inspect the quality of prefabricated housing units (Tan et al., 2020). The scanned data then automatically compares to the BIM model to perform inspection. Overall, BIM technology provides a well-organised information repository for quality management through both conventional and innovative methods. In terms of the cost, the object-oriented data structure in BIM models provides a comprehensive mechanism for quantity surveying and cost estimation (Plebankiewicz et al., 2015). In particular, quantity, volume, area, or length can be extracted directly from the BIM elements. For the items which are not built in the BIM model, various approaches and algorithms are proposed to deduce the approximate quantities and costs from the BIM model (Aibinu Ajibade & Venkatesh Sudha, 2014; Smith, 2016). Furthermore, schedule can be considered along with the process of the quantity surveying and cost estimation (Fan et al., 2015). This elevates the control of cost and schedule during the construction stage. Lastly, regarding human resource, BIM powers the platforms for collaboration which involves the interoperability of project information (Grilo & Jardim-Goncalves, 2010). This establishes a common understanding of the progress along with the project lifecycle. Besides, worker safety such as fall hazards is a serious issue on site. By leveraging the BIM technology, dangerous zones and safety codes could be planned and checked automatically in the virtual world before the construction (S. Zhang et al., 2015). In short, the consolidated information in BIM models serves as the foundation for the abundant applications in the construction stage.

After the construction is completed, the building needs regular maintenance to keep it functional and livable. BIM technology can be adopted in multiple application scenarios including facility management, operation and management, and emergency. Regarding facility management, facilities' information and sensor data can be integrated into the

BIM model for real-time monitoring (Arslan et al., 2017; Jun Wang et al., 2013). Once the equipment has problems, information then can be queried from BIM models to have a better understanding of the situation (D. Zhang et al., 2019). Besides, for the operation and management, assets management and building automation can utilise BIM models to keep the information spatially organised which assists the acquisition of information for routine maintenance (Edmondson et al., 2018; Pocock et al., 2014; Shalabi Firas & Turkan Yelda, 2017). To prepare for the emergency, the evacuation can be simulated in the BIM environment. For example, a serious VR game was designed for fire evacuation (B. Wang et al., 2014). The evacuation guidance is provided to train and raise the emergency awareness. Also, when a fire emergency happens, the evacuation system can be integrated with the indoor positioning system to provide dedicated evacuation guidance for each occupant in the building (N. Li et al., 2014). In conclusion, BIM technology is versatile for every application in the maintenance stage.

Table 3. BIM integrations across building lifecycle

Stage	Application	Research
Planning	Feasibility	Cost assessment - (Campisi et al., 2020; F. K. T. Cheung et al., 2012) Safety assessment - (Campisi et al., 2020) Sustainability - (Carvalho et al., 2021; Solla et al., 2019)
	Design	Visualisation - (Röck et al., 2018) Design review process - (Donato et al., 2018) Decision making improvement - (Giel, Brittany K. & Issa, Raja R. A., 2013)
	Analysis	Energy analysis - (Salman Azhar & Brown, 2009) Structural analysis - (F. Tang et al., 2020)
Construction	Schedule	Automatic scheduling - (ElMenshawy & Marzouk, 2021; Z. Wang & Azar, 2019) Progress monitoring - (Rebolj et al., 2017) Delay mitigation - (C. Z. Li et al., 2017)

	Quality	Collaboration - (Ma et al., 2018) Inspection - (Liu et al., 2021; Mirshokraei et al., 2019; Tan et al., 2020)
	Cost	Cost estimation - (Fan et al., 2015; Plebankiewicz et al., 2015) Quantity surveying - (Aibinu Ajibade & Venkatesh Sudha, 2014; Smith, 2016)
	Human resource	Collaboration - (Grilo & Jardim-Goncalves, 2010) Safety - (S. Zhang et al., 2015)
Maintenance	Facility management	Repair - (D. Zhang et al., 2019) Monitoring - (Arslan et al., 2017; Jun Wang et al., 2013)
	Operation and management	Building Automation - (Shalabi Firas & Turkan Yelda, 2017) Assets management - (Edmondson et al., 2018; Pocock et al., 2014)
	Emergency maintenance	Fire outbreak - (N. Li et al., 2014; B. Wang et al., 2014)

One of the advantages of applying BIM is the visualisation of design for checking the design intent (Arayici et al., 2011). Specifically, owing to the 3D nature, non-geometric data in the BIM model can be easily linked, providing a spatial view of project information. In other words, sensor values could be added or linked to BIM elements, strengthening the connections between geometric and non-geometric data. Besides, because of various needs of the project information, approaches for visualising sensing data normally vary with the scenarios.

Generally, there are three types of visualisation for sensing data including colour-coding on 3D models or 2D sheets, presenting on charts, or demonstrating in digital twins. Firstly, sensor data is colour-coding either on BIM elements or the zones in the building spaces. For example, in order to monitor the energy performance, lighting and people movements are collected by sensors and colour-coded on 3D zones (H. Wang et al., 2013). Temperature, ambient light, and humidity values are colour-coded on room objects of BIM models (Rogage et al., 2019). These provide an intuitive interface for understanding the energy performance of the building. In some cases, a colour scheme setup on 2D drawing is applied to simplify the presentations. For instance, in the facility management scenarios, there is a large amount of sensor data generated from the equipment. The sensor data can be simplified by applying colour scheme setups on multiple 2D drawings (Suprabhas & Dib, 2017). Afterwards, the colour-coded drawings are dedicated to specific maintenance usage with less visual interference. Second of all, in order to explore the details of sensor data, types of charts are normally chosen to compliment the colour-coding results. For instance, in the safety monitoring scenario on site, sensor values are plotted on charts for quantifying the hazards of the temperature and oxygen extremes (Riaz et al., 2014, 2017). Lastly, the sensor data could reflect the physical environment by providing digital twins. For example, a BIM- and sensor-based approach is proposed to assist the operation of tower cranes (G. Lee et al., 2012). By showing the digital twins of the tower cranes on site, operators can understand the crane's surroundings simultaneously. Blind spots which are often a problem during lifting operations are eliminated. In short, the aforementioned approaches exemplify the scenarios of leveraging sensor data. These help identify the suitable presentation of field sensing data in this research.

2.2 Work Packaging for Information Management

In this section, approaches for managing project information are reviewed including principles of work packaging, techniques of network analysis, and principles of lean construction. The reviews explore the solutions for gathering and managing information along the project lifecycle. Besides, the relationships among the information could be further analysed. These help design the approach for strengthening the information linkages.

2.2.1 Work Packaging principles

Work packaging is a process based on work breakdown structure (WBS). It breaks down the construction processes into manageable work packages whose cost and duration can be estimated and managed (Construction Industry Institute, 2013). By leveraging the technique, the project could be sketched in the early phase and then the work packages are refined progressively along with the project lifecycle (Alleman et al., 2017; Isaac et al., 2017). It is worth noting that the mechanism of work packaging and WBS is similar, but the concept is essentially different. The work packaging focuses more on the deliverables. Geometric and non-geometric details may be added to their corresponding work packages. It keeps the uncertainties at the early phase as long as the cost and duration can be estimated. During the project lifecycle, stakeholders can follow this unified layout of work packages to maintain the integrity of information. This provides a broad view of the tasks for stakeholders in a non-geometric manner. Furthermore, the process of information flow from designers to contractors and to subcontractors can be modeled, as every piece of information is stored in a unified and hierarchical structure.

Creating work packaging in a proper size is a challenge. In fact, many research studies aim at the mechanism of effectively creating work packages (Kim et al., 2008; X. Li et al., 2020; Raz & Globerson, 1998). The work packaging principles evolved into several planning and execution approaches for capital and industrial projects. For example, advanced work packaging (AWP) was implemented in the piping installation project to provide guidelines for a construction-ready deliverable (Guerra & Leite, 2020). Work packaging is an overall process flow targeting to organise information across project lifecycle. Generally, AWP consists of three types of work packages which are construction work packages (CWPs), engineering work packages (EWPs), and installation work packages (IWPs). The conceptual information model for work packages is illustrated in Figure 5, and a construction work package is exemplified in Figure 6. These three work packages are created by stakeholders in different stages and store different aspects of information. For instance, a logical and manageable division of work is defined in a CWP which is aligned with the project execution plan. Engineering and procurement deliverables corresponding to a CWP are specified in various EWPs. A predictable, measurable and efficient manner for a construction work crew is recorded in an IWP for each EWP. Regarding the stages for implementation, three stages are concluded, namely preliminary planning and design stage, detailed engineering stage, and construction stage. Owners, designers, construction managers, and subcontractors, who are the main stakeholders within a project, manipulate corresponding work packages in different stages. In fact, many case studies were conducted to testify the capability of AWP techniques in a project. Some case studies indicate that even though only part of the AWP hierarchy is adopted, the structural information helps manage the project information. Besides, they also state that a digitised AWP system may help accurately organise project information (Construction Industry Institute, 2013). Therefore, due to the hierarchical structure of AWP, information and pertinent documents across all project lifecycle could be accessed in an organised way which establishes a solid foundation for communicating across project lifecycle.

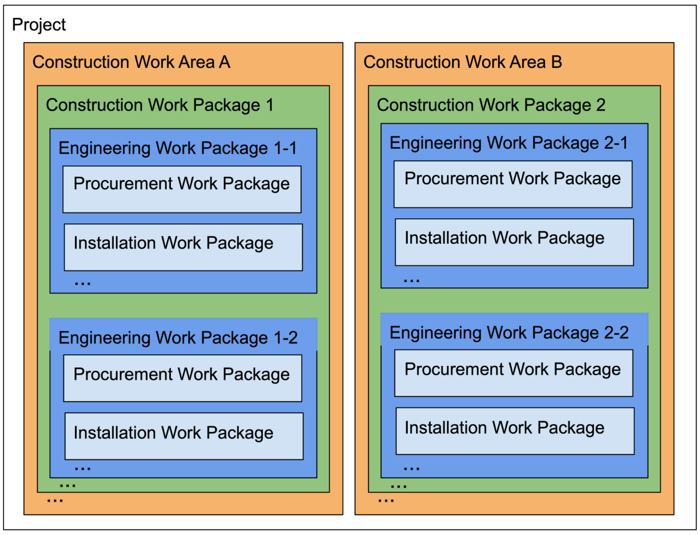


Figure 5. Information structure of AWP

The gap between the engineering and construction model was identified, and the gap could be further bridged by a contractual 3D model execution plan. In terms of the cost-effectiveness of the implementation, a systematic approach was developed to assess the cost and benefits of AWP implementation (Halala & Fayek, 2019). Generally, the savings in schedule and costs could be achieved through the implementation. Some research studies focus on the enhancement of work packaging to assist the information integration of specific tasks in the process. For example, a smart work packaging approach was developed to manage constraints during the production of prefabricated buildings (X. Li et al., 2019). Crane paths could be planned autonomously without collisions and dynamically updated based on the dynamic constraints in work packages. The approach assists crane operators in making adaptive path re-planning decisions. In short, stakeholders could leverage the work packaging to integrate multiple sources of information in order to improve the information flow of the project.

CONSTRUCTION WORK PACKAGE								
Project Name: Construction Repair Work						COMPANY LOGO		
Project CWP WBS No: 1.3.3.6 Structural Remediation Works								
CWP		**Plant**		**Area**		**Discipline**		**Sequence No**
C W P	-	0 0 0 1	-	A	-	Structural Engineering	-	0 0 0 1
Description:	Structural Remediation Works for Preheater Tower							

Table of Contents			
Section No.	Section Description	Section No.	Section Description
1.0	Scope of Work	12.0	Scaffolding
2.0	CWP Reference List	13.0	Special Equipment, tools and consumables
3.0	Engineering Information	14.0	Waste Management
4.0	Craft / Manpower	15.0	Risk Register
5.0	Direct Field Equipment and Materials	16.0	WorkFace Planning
6.0	Safety	17.0	Project Controls
7.0	Quality	18.0	Turnover Documents
8.0	Regulatory Approvals and Permits	19.0	3D Model Shots of CWP
9.0	Sub-contracts (Construction Contractor)	20.0	Submittals
10.0	Vendor Support	21.0	Contact List
11.0	Rigging Studies		

12.0 SCAFFOLDING

12.1 Scaffolding Plan

Provide the estimated scaffolding types, location, duration and quantity requirements (including materials and labor) for the scope of work associated with the CWP.

1. Install Temporary Scaffold Access Tower East Side Of Preheater Tower From RL 4,630 To RL 44,232.
2. Install Scaffold Loading Bay To RL 44,232.
3. Install Temporary Scaffold Access Tower East Side Of Preheater Tower From RL 44,232 To RL 53,092.

Floor plan: Plan_A_RL44232.dwg
Duration: 15 days

Figure 6. Example of a CWP for structural remediation works

2.2.2 Network Analysis

Network analysis is the process of gathering data and illustrating the relations. The process involves several integrated techniques to analyse the structure and interdependencies. It is widely used in various scientific areas because of its capability of discovery of inter-relations (Z. Wu et al., 2019). For example, trends and current gaps are identified regarding the BIM-based projects (Oraee et al., 2017; Z. Wu et al., 2019).

Relations among literatures and their research teams are identified by network analysis to point out the areas where the majority of efforts are put. It also highlights the research topics which top researchers are interested in.

Key factors or stakeholders of the process could be identified through the network analysis to provide an insight for improvement. For instance, the interdependencies among various legal aspects in BIM contracts are investigated (Fan et al., 2019). The analysis shows that roles and responsibilities for each stakeholder are the key aspects associated with BIM contracts. Besides, central stakeholders among the collaborative relationships in the project lifecycle could be mined through the network analysis (Y. Wang et al., 2020). It provides a quantitative approach to discover successful characteristics in the collaboration. In addition, because of the large amount of information in BIM models, relationships among the information could be analysed to improve the design. For example, the disassembly impact of the design is evaluated through the network analysis (Denis et al., 2018). By utilising the information of building elements in BIM models, material loss and disassembly time are identified which supports decisions during the design process. In brief, network analysis enables the discovery of relationships among data. This helps examine the project information and give potential to establish the relationships among the information.

2.2.3 Lean Construction

Regarding the information management workflow, lean design and construction principles aim to minimize waste during collaboration. These principles suggest that the last planner system (LPS) should be adopted, which leverages social methods to clarify dependencies from stakeholders (Aziz & Hafez, 2013). Specifically, pull planning, a technique used as a part of the LPS, includes stakeholders who are directly responsible for supervising tasks. Stakeholders start planning with the end goal of the project and work backwards milestone by milestone. This process maximizes stakeholder engagement to collaboratively determine the available plans. The implementation of lean principles has validated that the information waste is removed by scheduling accurate information requirements along the project lifecycle (Uusitalo, Seppänen, Peltokorpi, et al., 2019). For instance, Figure 7 shows the five stages of the LPS adopted in the construction projects (AlSehaimi et al., 2014; Ballard & Tommelein, 2016). The first two stages are mainly for long-term planning which includes identifying milestones, establishing promises, sketching collaborative plans and handoffs. On the other hand, the last three stages focus on short-term planning. The collaborators look ahead six weeks to eliminate any constraints and ensure the promises could be delivered on time. Besides, the performance is quantified such as planned percent complete (PPC) reviewed by coordinators regularly to prevent recurrence in the process. Apparently, a great amount of project information needs to be acquired in these stages. By leveraging the information integrated by BIM, it has been pointed out that the BIM-based collaborative environment further minimizes tangible and intangible waste in the construction project (Heigermoser et al., 2019; Radl & Kaiser, 2019). Specifically, the planned quantities of materials and the productivity of the workforce are evaluated based on the properties of building components. Then, after comparison between the planned to the as-built quantity and productivity in element level, the largest amount of waste could be determined and be minimized in the lean process. In short, there is no doubt that the lean construction minimizes the waste by itself in the process. Furthermore, the abundant integrated information supported by BIM, including geometric and non-geometric data, elevates the details of evaluation for quantity and productivity in each stage and provides the opportunity for further improved lean practices.

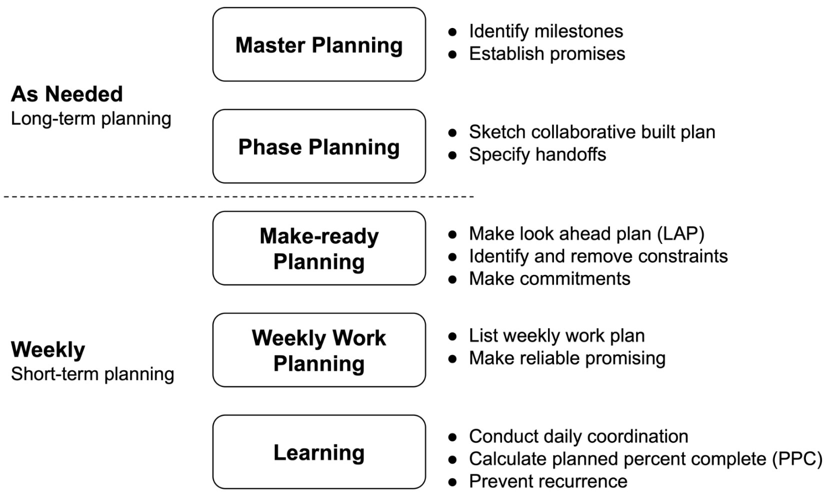


Figure 7. Stages of last planner system

A lean design management is integrated with BIM-based projects to explicitly define the maturity of BIM models. For example, a location-based design management process leveraging the level of details of BIM models and LPS was developed (Uusitalo, Seppänen, Lappalainen, et al., 2019). Specifically, requirements of the end-user in each stage of the construction are defined and serve as the definition of level of detail (LOD). The approaches clarify the information needs from project stakeholders and increase the common understanding of the project which potentially reduces the waste by scheduling precise LOD of BIM models. Additionally, except for applying lean construction in the construction process, the idea is carried out in prefabricated production as well (Hopp & Spearman, 2004). Information from production, logistics operations, and site assembly is integrated by pull production and 4D BIM models (Bataglin et al., 2020). The application streamlines the high degree of complexity from the interdependencies among the production, logistics, and construction processes. In short, the research could leverage the lean construction to standardise the works in multiple processes which assists the information management while collecting project information.

2.3 BIM-based Common Data Environment for Information Collaboration

In this section, technologies and standards for establishing a data environment along with the project lifecycle are reviewed. The literature reviews cover the topics of cloud-based BIM applications, techniques of cloud computing, standards of data environment, and standards of the collaboration workflow. It helps develop a comprehensive collaborative environment to facilitate the information flow from each stakeholder.

2.3.1 Cloud BIM

BIM techniques are widely used for information management purposes in the AEC industry by providing integrated geometric and non-geometric information (Salman Azhar, 2011; Demian & Walters, 2014). The geometric and non-geometric data are stored or linked to elements in the BIM model, which helps stakeholders better visualize or manipulate the project data (S. Azhar et al., 2008; J. Wang et al., 2014). Many studies have attempted to implement BIM techniques into a variety of scenarios to improve the efficiency of information management (X. Li et al., 2018; Manning & Messner, 2008; Volk et al., 2014; P. Wu et al., 2016). For example, Hallberg and Tarandi (Hallberg & Tarandi, 2011) demonstrated several case studies on the capability of BIM technologies in lifecycle management related to information visualization. The BIM-based tools used in these cases serve as an information repository. They demonstrate that 3D or four-dimensional (4D) building information helps to visualize and communicate building information, improving the reliability and efficiency of building processes. A high-speed rail project in Taiwan also verified that the 3D visualized interfaces improve efficiency during the troubleshooting process (W. Lee et al., 2015). The BIM model serves as an information integrator to achieve coordination among multiple construction sectors. Therefore, stakeholders could leverage the capability of BIM technologies, especially visualization, to improve the communication within the project lifecycle.

To handle the progressive elevation of stakeholders' engagements in information management, it is suggested that cloud-based BIM systems be adopted due to their scalability, accessibility, and real-time communication capability. For instance, document management, user authorization, and workflow management have been implemented into a cloud-based system to improve the accessibility of project documents and increase the level of participation from stakeholders (Ding & Xu, 2014). To expand the boundaries of communication, BIMCloud provides information sharing on partial BIM models (Das et al., 2015; Moumita et al., 2014). The designed schema integrated with the BIM model could capture the data from the interactions, which serves as the essential knowledge along with the project lifecycle. Therefore, it has been found that cloud-based BIM technology would undoubtedly have a profound effect on BIM applications (Wong et al., 2014). In short, cloud-based BIM applications support the scalability and accessibility which are the essential needs in collaboration scenarios. The BIM-enabled approach could be beneficial to implement the cloud BIM technology. Afterwards, diverse stakeholders are able to be involved in the collaborative processes.

2.3.2 Software As A Service

Software as a service (SaaS), platform as a service (PaaS), and infrastructure as a service (IaaS) are three types of software distributions powered by cloud computing. Specifically, SaaS provides rental softwares for users by service providers which host the service on a central network server. Users are able to select the service based on their demands in the pay-as-you-use business model (Loukis et al., 2019). Next, PaaS aims to provide a versatile environment for developers to customise their applications (Verba et al., 2017). Developing, testing, running, and managing the applications could be done on the platform which simplify the maintenance of the infrastructure. Lastly, IaaS provides virtual hardwares such as physical computing resources or data partitioning (Fady & Hemayed, 2019). Developers are able to access the low-level of network infrastructures such as virtual machines, firewalls, IP addresses, or load balancers.

It has been pointed out that the AEC industry could benefit from the SaaS of cloud computing (Underwood & Isikdag, 2011). The reason is that applications from multiple stakeholders and stages along with the project lifecycle could be hosted and integrated through a distributed environment and virtual data centres. For example, instead of hosting all relevant data in one super schema, private cloud platforms were developed to virtually integrate the information from multiple stakeholders who store the data in their own servers (Redmond et al., 2012; J. P. Zhang et al., 2014). The efficiency and quality of data extraction and delivery are improved. Therefore, the collaborative design of this research could leverage the power of SaaS for information integration.

2.3.3 Common Data Environment

With the development of collaborative applications, the common data environment (CDE), which is a central repository housing disseminated documentation, has been adopted for geometric and non-geometric data to clarify the responsibility, liability, and ownership of data (Radl & Kaiser, 2019). The concept is further standardized by the Construction Industry Council as a BIM protocol aiming to offer contractual arrangements (Construction Industry Council, 2018). In the protocol, the obligations for providing and sharing information using a CDE are specified. Therefore, by following the protocol of CDE, the collaborative design in this research could be clearly defined and suitable for multiple types of stakeholders. An example of BIM- and CDE- enabled facility management also aligns with the statements (Patacas et al., 2020). The challenges of information management in facility management and maintenance due to the lack of structured information framework could be solved. Asset information models are built to integrate the distributed data sources.

2.3.4 ISO 19650

In terms of the deliverables and workflows, the International Organization for Standardization (ISO) 19650 series identifies the information requirements in the delivery cycle and the required capabilities and capacities of the delivery teams (International Organization for Standardization, 2018a, 2018b). This standard achieves collaboration with a mutual understanding among stakeholders. Overall, with the implementation of a CDE, a single source of information could be established that facilitates collaboration and avoids duplication during the information management process. The organized information could support the further analyses or decision-making processes as well (H. Li et al., 2017; Qu et al., 2020; Song et al., 2019).

Chapter 3: Research Methodology

This chapter introduces the contents, methods, and expected outcomes of each objective outlined in Section 1.3 respectively. To have a comprehensive view of this research, Figure 8 illustrates the methodology of the research objectives. To start with, in Objective 1, the sensing capability (Figure 8a) is examined in terms of the read range and angle. The examination supports the practical usage of sensing technology in the corrosion prediction scenario (Figure 8b). The outcomes of the application then summarise in a field sensing framework (Figure 8c) for further research and support the field sensing module (Figure 8d) of common data environment. Secondly, in Objective 2, the information flow is investigated (Figure 8e) to build the foundation of the BIM-enabled work packaging approach. Additionally, the structural refurbishment project (Figure 8f) is selected to evaluate the proposed approach. The investigation and the project support the outline of a BIM-enabled work packaging framework (Figure 8g), and the framework contributes to the data management repository (Figure 8h) of the common data environment. Lastly, in Objective 3, an integrated framework of the common data environment (Figure 8i) is concluded to leverage the outcomes from Objective 1 and 2 in multiple scenarios of project management. A construction inspection scenario (Figure 8j) and a change impact scenario (Figure 8k) are conducted to show the effectiveness of the improvement of information flow in the proposed framework.

In terms of the research design, Figure 9 provides a holistic view of each research objectives and the relationships among them, and the details of each objective are elaborated in the following sections.

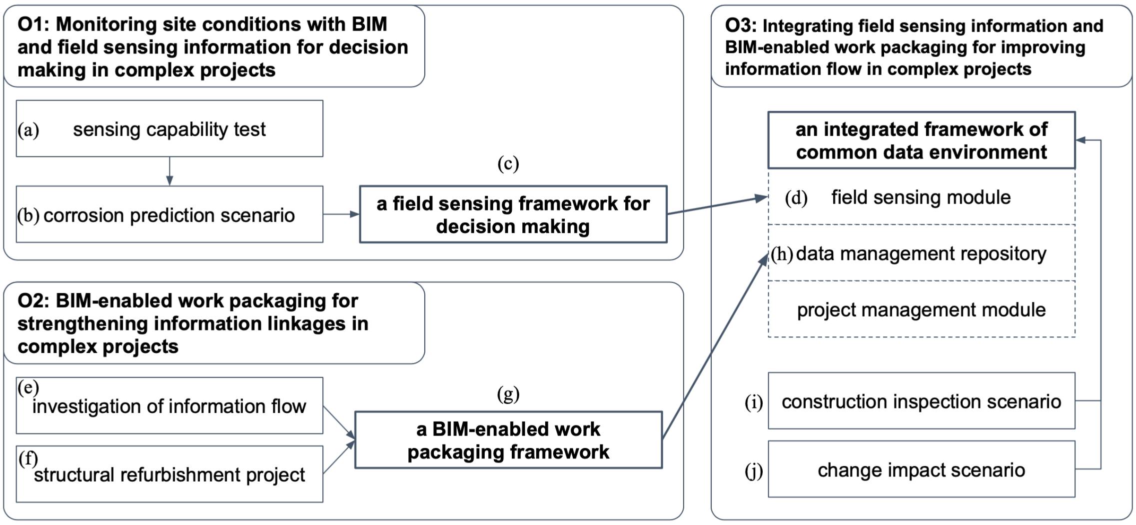


Figure 8. Research methodology for each objective

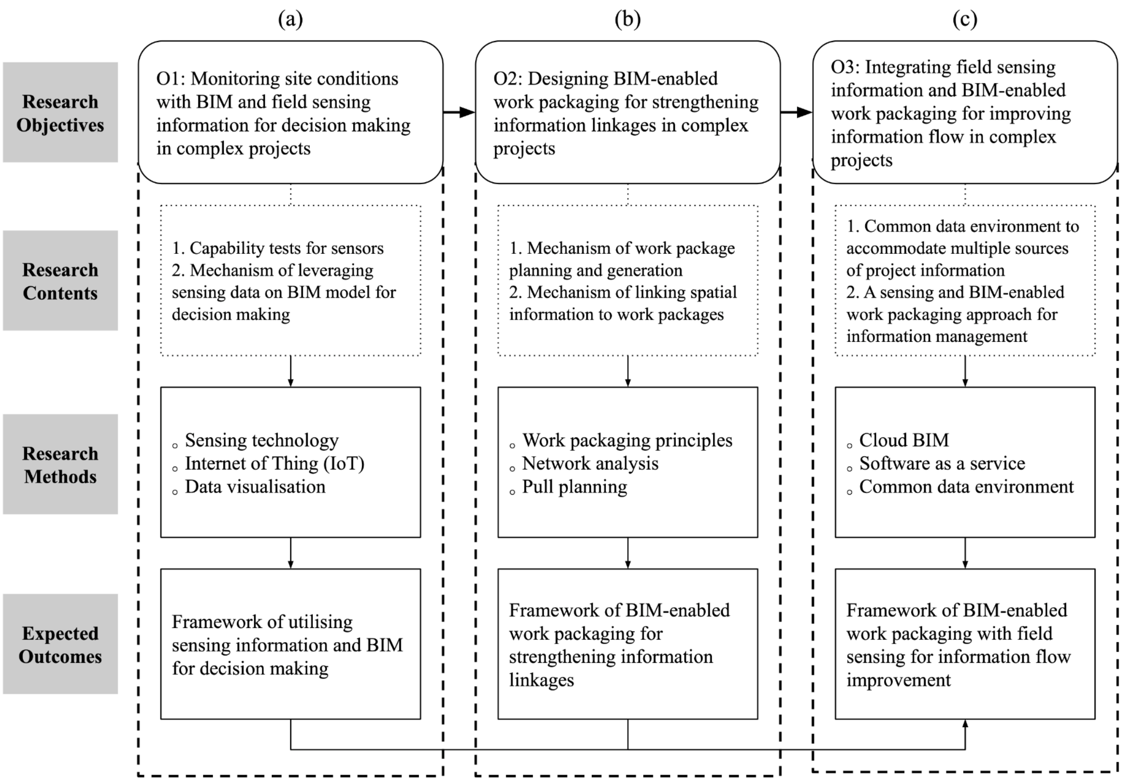


Figure 9. Research design for each objective

3.1 Developing BIM-enabled Site Monitoring for Decision Making

Smart sensing technologies were examined at the beginning to understand which technologies are suited for the environment on construction sites (Section 2.1.1, Chapter 2). The examination provides an insight to continuously collect site information which suffices the information needed for decision making. Afterwards, BIM and Internet of Things (IoTs) technologies were investigated (Section 2.1.2, Chapter 2) as well to identify possible approaches to integrate site information and project information for decision making. Then, the solutions of data visualisation enabled by sensing information and BIM models were reviewed to understand the approaches of utilising sensing information and analytic results in decision making processes (Section 2.1.3, Chapter 2). Subsequently, a BIM-enabled site monitoring framework for decision making was designed which consisted of three major modules: (1) Data collection module, (2) Data analysis module, and (3) Application module. An experimental testbed was built upon the approach following the proposed framework. The capability tests for selected sensors were conducted to understand the read range and read angles of the sensors. Besides, each module inside of the framework was evaluated respectively to verify the practicality and potential limitations of the proposed framework. A detailed description of the framework and validation are illustrated in Chapter 4. The research design for developing a BIM-enabled site monitoring approach for decision making is summarised in Figure 9(a).

3.2 Developing BIM-enabled Work Packaging for Information Linkages

Two types of information management methods including work packaging principles and pull planning were examined firstly (Section 2.2, Chapter 2). Sources of information from stakeholders along with the project lifecycle are identified and the mechanism of organising this information are investigated as well. The review benefits the design of strengthening information linkages because the scope of information in a project is outlined and the structure of project information is illustrated. Afterwards, a framework of BIM-enabled work packaging for strengthening information linkages was developed which contains four modules: (1) Data preparation module, (2) work package planning and generation module, (3) work package linking module, and (4) work package updating module. An experiment from the structural refurbishment project was performed to verify the effectiveness of strengthening information linkages. Details of the framework and its validation are elaborated in Chapter 5. Finally, the research design for strengthening information linkages is summarised in Figure 9(b).

3.3 Designing Common Data Environment of Project Information Management

Both information technologies and information management standards were reviewed (Section 2.3, Chapter 2) to explore the solutions for a versatile project data environment. In terms of the information technology, information infrastructures of the cloud BIM applications were investigated to compare the flexibility for different applications. Mechanisms of Software as a Service (SaaS) were studied to find the best practice for project information management. Furthermore, regarding the information management standards, the principles of establishing a Common Data Environment (CDE) and International Organisation for Standardisation (ISO) 19650 series were reviewed to leverage the outcomes from Objective 1 and 2 which already organises the information of site conditions and from stakeholders for improving information flow along the project lifecycle. Subsequently, a CDE for improving information flow was designed consisting of three major modules including: (1) Field sensing module, (2) data management repository, and (3) project management module. Two pilot studies were tested to demonstrate the information management capability of the proposed CDE in different scenarios. The detailed elaboration about the common data environment and the exemplifications are covered in Chapter 6. The research design for the CDE is shown in Figure 9(c)

Chapter 4: Monitoring Site Conditions with BIM and Field Sensing Information for Decision Making in Complex Projects

4.1 Introduction

Construction site is a challenging environment for utilising sensors because of the characteristics of no power supply and severe working environment. Namely, sensors may need to have built-in power supply, and be installed underground, in the water, or working in high temperatures. The situation narrows the selection of applicable sensors. Besides, the sensor data needs to be interpreted, arranged or analysed, especially integrated with BIM models, before the decision making. Accordingly, decision makers can be well-informed about the site conditions. A framework that lays out the technologies, considerations, approaches for field sensing is vital. In particular, the framework should cover the main concerns including how the sensor data is sent from site to office, how the sensor data is arranged or analysed, and how decision makers can leverage the outcomes of sensor data?

Chapter 4 proposed a BIM and field sensing framework to leverage the site information with BIM for decision making (Research Objective 1). The framework consists of three major components including data collection module, data analysis module, and application module as shown in Figure 10. These components cover the details of applying the approach from sensor selection, data integration methods, to analytic results visualisation. An experimental testbed was selected to demonstrate and verify the feasibility of the framework. The results show that a successful implementation of the framework benefits the decision making process by an straightforward interface of utilising on site information.

4.2 A Framework of Leveraging BIM and Field Sensing for Decision Making

A framework leveraging the power of BIM, analysis model, and sensing technologies is developed. Sensor values and elements' properties could stream to the system as inputs for the analysis model. Then, the analytic results could be visualised in a 3D environment powered by BIM technology. These could help identify the target area for the application.

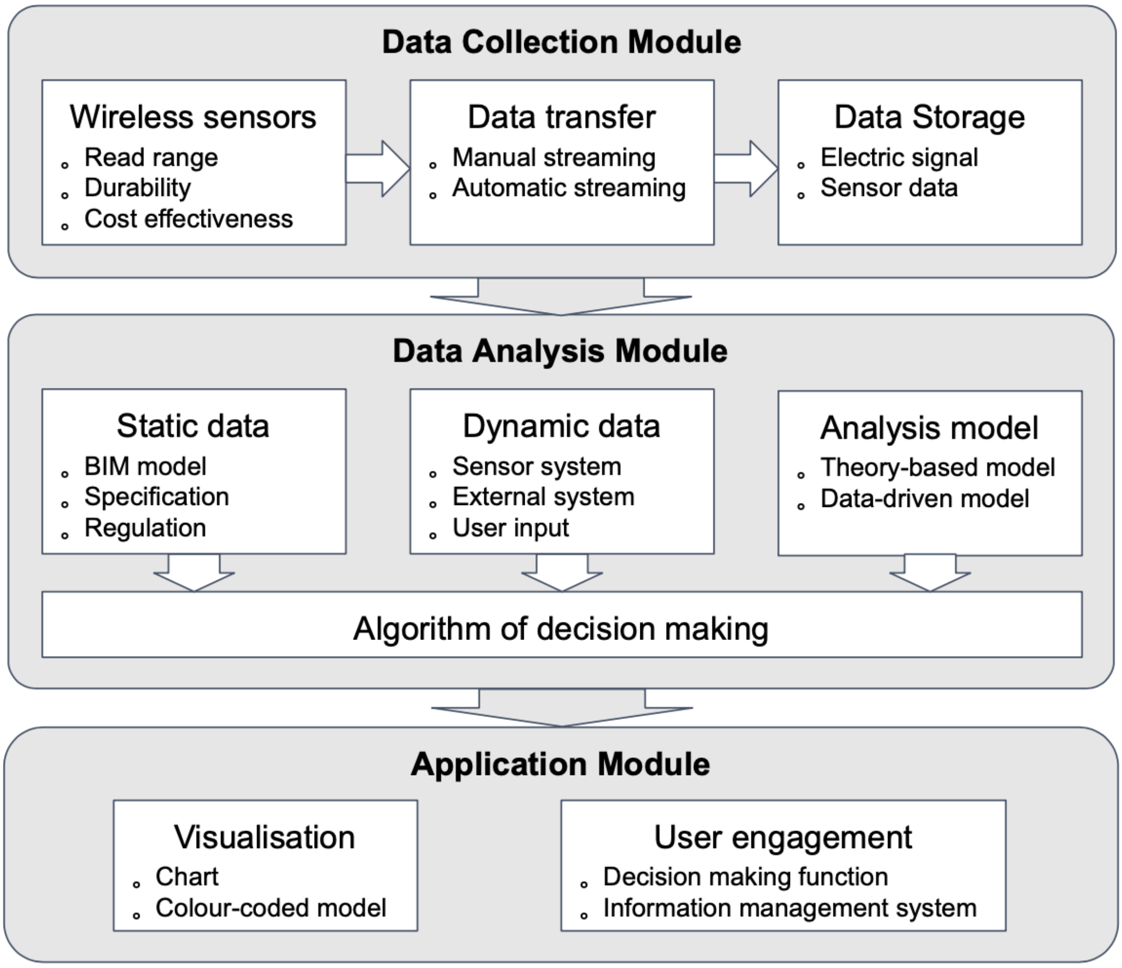


Figure 10. Framework of leveraging BIM and field sensing for decision making

4.2.1 Module 1: Data Collection

For the data collection module, types of sensors, how the data be transferred and stored should be considered. Due to the large scale of the project site, how to install or maintain sensors should be considered while selecting sensors. Read range, durability, and cost effectiveness are the three criteria for choosing sensing technologies. Long read range is normally needed on a site because it could save lots of manpower while collecting sensor data. On that account, RFID sensors working in ultra-high frequency (UHF) which is normally around 900 (MHz) are preferred. The reason is that read range and working frequency are positive-correlation. Higher working frequency could result in better read range. Besides, the size of antenna on sensors is relative to read range. It is better to select a large antenna for better read range; however, the size and shape of the antenna may influence the applicability on site. Therefore, the selection of antennas should balance the needs of read range and the application scenario. Next, durability of the sensors is of much concern in industry. In fact, batteries, the power of sensors, are the major factor for durability. In order to maximise the durability, passive sensors which collect energy from nearby readers are widely utilised in industry. However, the power of passive sensors is relatively small compared to active sensors. Chips on the passive sensors should be energy-efficient which limits the functions of sensing. Regarding cost effectiveness, sensors with long read range and durability could reduce the cost. On the other hand, the more applications benefited from the sensor data could increase the value of sensors which results in increasing the cost effectiveness. Both reducing the implementing cost and increasing the value of sensors are essential while considering the cost effectiveness in industry. In short, read range, durability, and cost effectiveness are three of the most important criteria while selecting sensors from an industrial perspective.

Next, manually or automatically streaming data from site to system should be considered. Assigning workers to patrol particular areas and collect sensor data could be easily implemented. However, data missing or a long period of sensing cycle may happen which results in the compromises of quality of the data. An effective method for managing the groups of workers may be needed. On the contrary, automatically collecting sensor data is robust. With an array of readers implemented on site, sensor data could be updated to the system up to every minute. In fact, the frequency of sensing may be crucial in some scenarios because some changes on site happen at a glance. For example, gas leaking on pipelines may only happen a few seconds but regularly. If the frequency of sensing is not intense enough, the leaking could not be noticed which could influence analysis.

In terms of data storage, both electrical signals as known as raw data and sensor value should be stored. The reason is that most sensor values are converted from the electrical signal which is generated from the sensor on tags. Specifically, when the environment changes, e.g. temperature changes or moisture changes, resistance on the sensor changes which results in electric current changes. Most sensors capture the changes and convert them to sensor values. Therefore, because of the indirect sensing method, the electrical signal could provide a better reference for calibrating the sensor values. Nowadays, because the technologies of local databases or cloud database services are mature, all sensor data can be stored in these databases effortlessly. Storing sensor data in local databases or cloud databases may be attributed to a business decision.

4.2.2 Module 2: Data Analysis

For the data analysis module, algorithms and their inputs should be considered. Typically, the sources of inputs are from BIM models and sensors which represent the source of static inputs and dynamic inputs respectively. Regarding the static data, BIM models could be a repository for elements' properties because most properties are already embedded in BIM models while modelling such as material and thickness of pipelines. Additionally, specifications and regulations could be utilised to identify constant variables dedicated to analysis models. By leveraging these static data, properties in BIM elements and variables from specifications or regulations could be collected as inputs for analysis models with less effort. For the dynamic data, the various inputs which analysis models depend on are from sensors. The inputs are streamed from sensors and updated frequently. Besides, dynamic data could come from external systems or user inputs. These could also be integrated into the analysis model to suffice the needs from the chosen algorithm. In short, static data and dynamic data serve as inputs for an analysis model. As regards to the analysis models, both theory-based algorithms or data-driven algorithms could be implemented for data analysis. In general, theory-based algorithms are modeled through experimental approaches. The algorithms could be applied intuitively because the inputs of the algorithm are defined. However, the assumptions or conditions of the theories may not fit the applications. On the other hand, data-driven algorithms leverage the emerging technologies of data science. Inputs or records could serve as training data to develop a machine learning model. The development of the data-driven algorithms may be complex but it could fit the exact scenario of the application. Briefly, either theory-based or data-driven algorithms could provide an analysis model for the application.

4.2.3 Module 3: Application

For the application module, the visualisation of analysis results and how the results support the inspection works should be considered. Regarding the visualisation, sensor data and the results from the data analysis module should be visualised through BIM technology. Charts can be provided and elements can be colour-coded by the scale of sensor values or analysis results to assist the decision making process. In terms of user engagement, suggestions could also be made by the information management system. The analysis results could provide straightforward advice to the decision makers which eliminates the potential of missing spots on site.

4.3 Case Study

4.3.1 Background

The proposed framework leverages sensors to collect the site conditions and stream to the office for decision making. The collected site conditions could be either the status of the environment on a construction site or the conditions of the facilities and assets depending on the monitoring targets, because the mechanism of monitoring, collecting and integrating sensor data is similar in construction and operational scenarios. Therefore, the framework could be applied in the construction stage through the operational stage. An operational scenario (corrosion management) is selected to demonstrate the feasibility of the proposed framework in Chapter 4. Besides, this framework is further integrated in the construction scenario in Chapter 6 which proposes a common data environment for project information management.

Corrosion under insulation is one of the most important issues in the petroleum industry. Ordinarily, in order to check the corrosion, inspectors remove the insulation of pipelines to measure the level of corrosion on each section of pipelines. This procedure may take weeks for a site which distinctly affects the financial aspect of oil and gas companies due to the pause production of its high-value products; therefore, in most cases, inspectors spot-check pipeline corrosion based on their experience. However, because the environments on sites are various, experience-based inspection may not be suitable for every site. On the other hand, even though inspectors want to access more data for better understanding of the site before the site trip, historical data sometimes are lost or scattered which leads to a hard situation for preparation of corrosion inspection. With the application of BIM and field sensing technologies, site data could be continuously collected and integrated into the BIM-enabled system. With the analysis of corrosion prediction, potential corroded areas could be highlighted on the BIM model.

The validation utilises passive RFID sensors, which are smart sensing technologies, to collect site data and then integrate them into a BIM system. A uniform corrosion model is also adapted from the theories of corrosion to leverage both sensor data and BIM elements' properties. They serve as inputs to calculate the corrosion rate which is the key value of corrosion prediction. Then, the corrosion prediction results are colour-coded on a BIM model which helps inspectors intuitively understand the prediction and prepare for the site inspection. In result, the proposed framework could provide a novel approach for decision making based on the monitoring of site conditions.

4.3.2 Process Modelling for the Approach for Corrosion Prediction

The process model of the proposed approach is illustrated in Figure 11 by implementing Business Process Modelling Notation (BPMN) tool (Dijkman et al., 2011). Specifically, how users interact with the system and the mechanism of the system are identified. Four groups in the process model including sensor implementation, sensor data streaming, data visualisation, and tasks for inspection are elaborated in the followings:

1. Sensor implementation: To start with, proper sensors are selected and the BIM model is prepared. Then, the sensors are codified to map the elements in the BIM model. Normally, general unique identifications in elements' properties are chosen for codifying sensors because they are unique and available in every element. After preparing sensors and BIM models, the BIM models should be uploaded to the system and stored in specific model databases for the following usage. Meanwhile, sensors could be attached to pipelines on site to finish the hardware implementation.

2. Sensor data streaming: Either manually or automatically transfer sensor data could be adopted while streaming the data from site to office. For manually collecting sensor data, workers are assigned to a specific area and requested to scan all sensors in that area. Afterwards, the workers need to upload the sensor data from the reader to the system. On the other hand, if fixed readers are installed, sensors are regularly read and the readers upload sensor values to the system automatically. No matter how sensor data is collected, the system processes the sensor data and saves these data into a raw signal database and sensor value database which is a readable value converted from raw signal.

Then, users could decide their operations for the sensor data.

3. Data visualisation: There are three operations while visualising the sensor data: visualising sensor data, visualising corrosion prediction, and visualising spot-check suggestions. First of all, sensor values are embedded in the corresponding elements in the BIM model by accessing the BIM model database and sensor value database. Therefore, elements could be colour-coded by the user-defined scale. Secondly, the sensor values and elements' properties are served as inputs for mathematical models of corrosion prediction. Corrosion rate could be calculated based on the inputs. With a given target date which is normally 3 to 5 years from present, BIM models could be colour-coded by the depth of corrosion. Lastly, based on the colour-coding of sensor values and corrosion prediction on BIM models, users can check the highlighted elements for better understanding of the site. Because a 3D environment is provided for visualising the suggested spot-check elements, 3D operations such as zooming, rotating, filtering models could be applied to help identify tasks for inspection.

4. Tasks for inspection: While deciding tasks for inspection, details of tasks could be planned and documented because lots of information is stored or could be referred through elements in BIM models. Most of the tasks are well-planned before the site trip. In addition, these tasks could be saved in a database and ready for on-site usage.

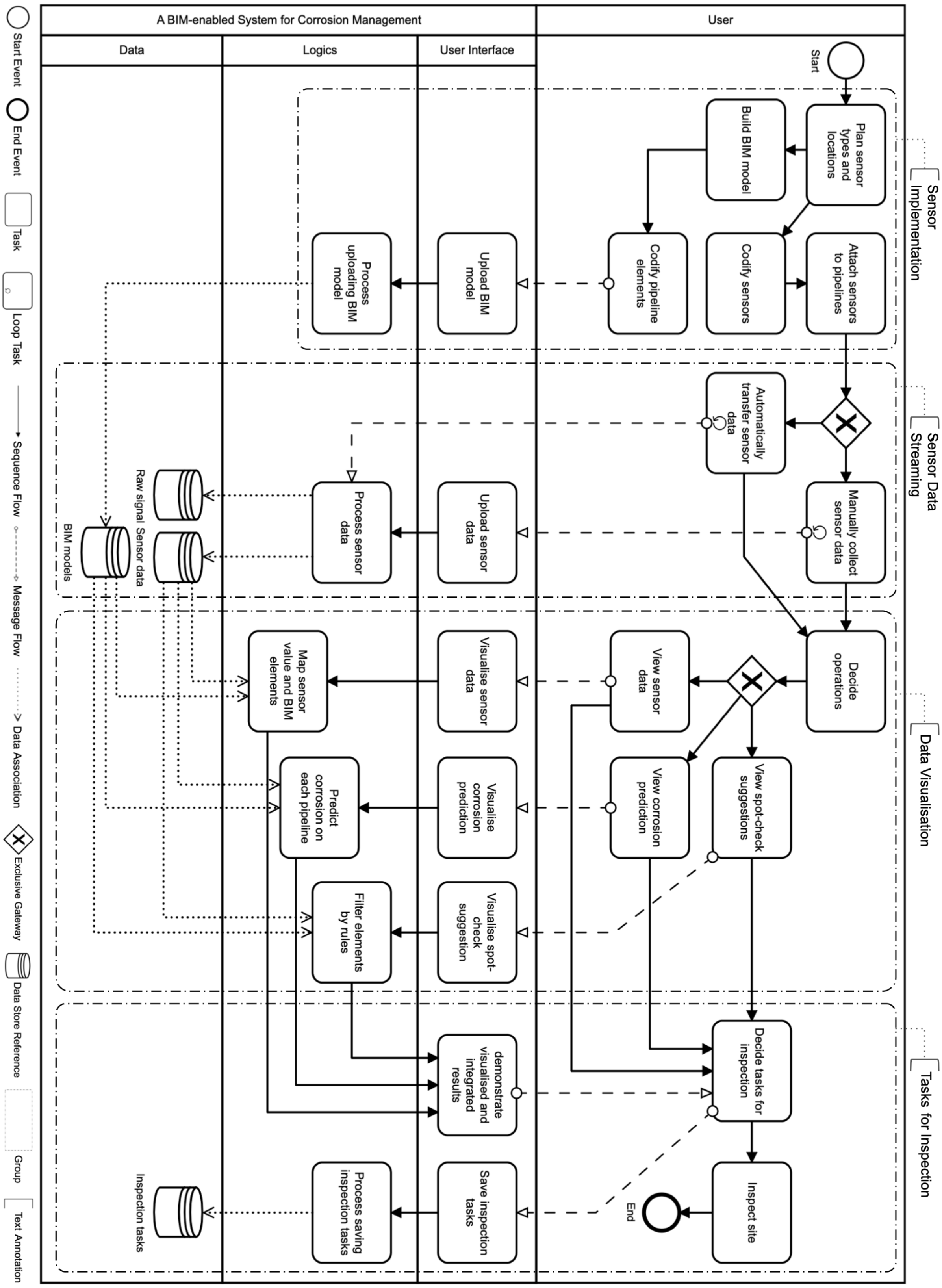


Figure 11. Process model of predicting corrosion under insulation

4.3.3 System Framework

Implementations of the proposed framework are shown in Figure 12. The framework consists of three modules: data collection with smart sensing technologies, mathematical model for corrosion prediction, and BIM-enabled external pipeline corrosion prediction.

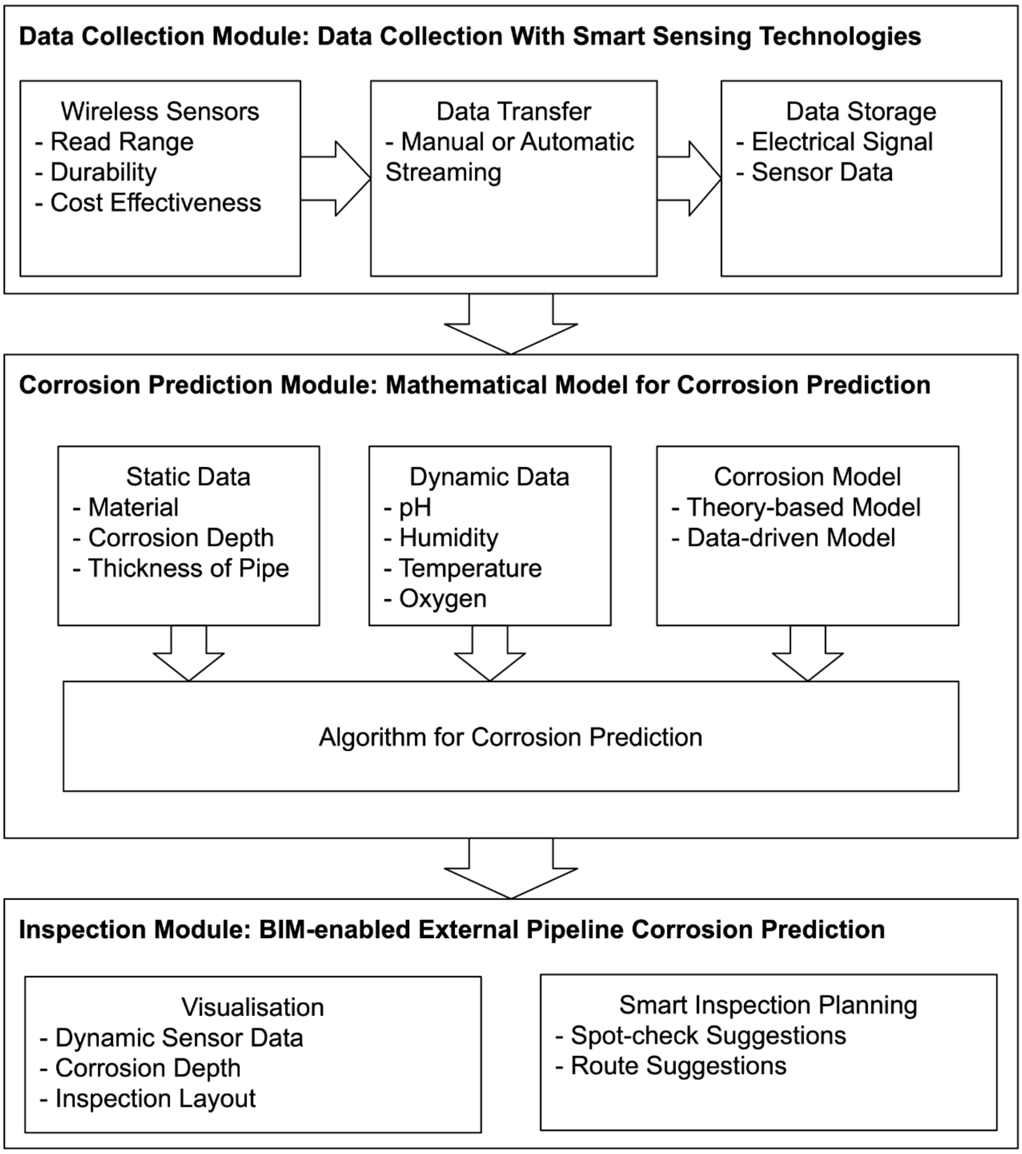


Figure 12. A BIM-enabled corrosion prediction framework

For the data collection module, RFID-based humidity and temperature sensors are chosen. These sensors are passive and designed for construction sites which means the sensors are energy-efficient and durable. Regarding the data transfer and storage, the configuration is shown in Figure 13. Fixed readers and antennas collect site data and the data hubs stream the information to the dashboard through the internet constantly. Both electrical signal and sensor data are stored in the databases located at the office.

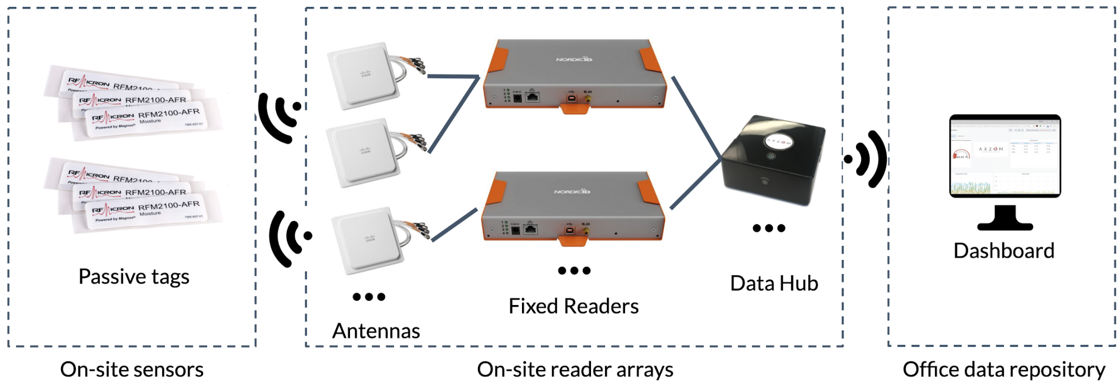


Figure 13. Hardware layout of BIM-enabled field sensing

For the corrosion prediction module, properties of elements in BIM models are selected as static data. Corrosion model could access the latest elements' properties which reflect the real site conditions. Various inputs which corrosion models depend on are from sensors. For example, humidity and temperature are the inputs of dynamic data for uniform corrosion models (Cottis, B., Graham, M.J., Lindsay, R., Lyon, S.B., Richardson, T., Scantlebury, D., Stott, H., 2010). The inputs are streamed from sensors and updated frequently. Therefore, static data and dynamic data serve as inputs for a corrosion model to predict the status of corrosion for pipelines. As regards the algorithms of corrosion model, theory-based algorithms or data-driven algorithms could be implemented for calculating corrosion rate which is used for corrosion prediction. As aforementioned studies, the fundamental of theory-based algorithms is chemical engineering. The process of corrosion is modeled through electrochemical or experimental approaches. On the other hand, data-driven algorithms leverage the emerging technologies of data science. Inputs and maintenance records could serve as training data to develop a machine learning model to help identify potential corrosion. Briefly, either theory-based or data-driven algorithms could provide a predictive model for corrosion prediction.

For the inspection module, regarding the visualisation and smart inspection planning, sensor data and the results from the corrosion prediction module should be visualised through BIM technology. Elements can be colour-coded by the scale of sensor values or corrosion depth. This could help inspectors identify the potentially corroded area. In addition, spot-check lists could be suggested by the system automatically. Routes of inspection could be schemed before site trips as well. These provide a straightforward plan for inspection which eliminates the missing of critical spots on site. This approach is consistent with other research studies which agree that the effectiveness and efficiency of inspection could be improved (Y. H. Tsai et al., 2014; Y. H. Tsai & Hsieh, 2016).

4.3.4 System Architecture

A system is developed on the basis of the proposed framework in order to validate the feasibility of the approach. Essential components are identified in the system architecture shown in Figure 14 To start with, RFID readers are chosen to read tags on site and communicate with sensor data hub in a local wireless internet environment. The sensor data hub integrates all reader's values and streams sensor values to the system through Hypertext Transfer Protocol (HTTP) requests. The web server located at the office processes the data streaming through HTTP requests. It acts as a gate to handle requests of inputs and outputs. Therefore, the web UI could get sensor data or analysed results from the web server to present the information in an user-friendly way. In addition, three main logics support the data processing and analysing which are the sensor data processing, algorithm for computing corrosion rate, and spot-check suggestion. To support the aforementioned logics, four databases are built: raw signal database, sensor value database, BIM model database, and inspection task database. The logics and related databases are the core of the approach which are derived from the proposed framework.

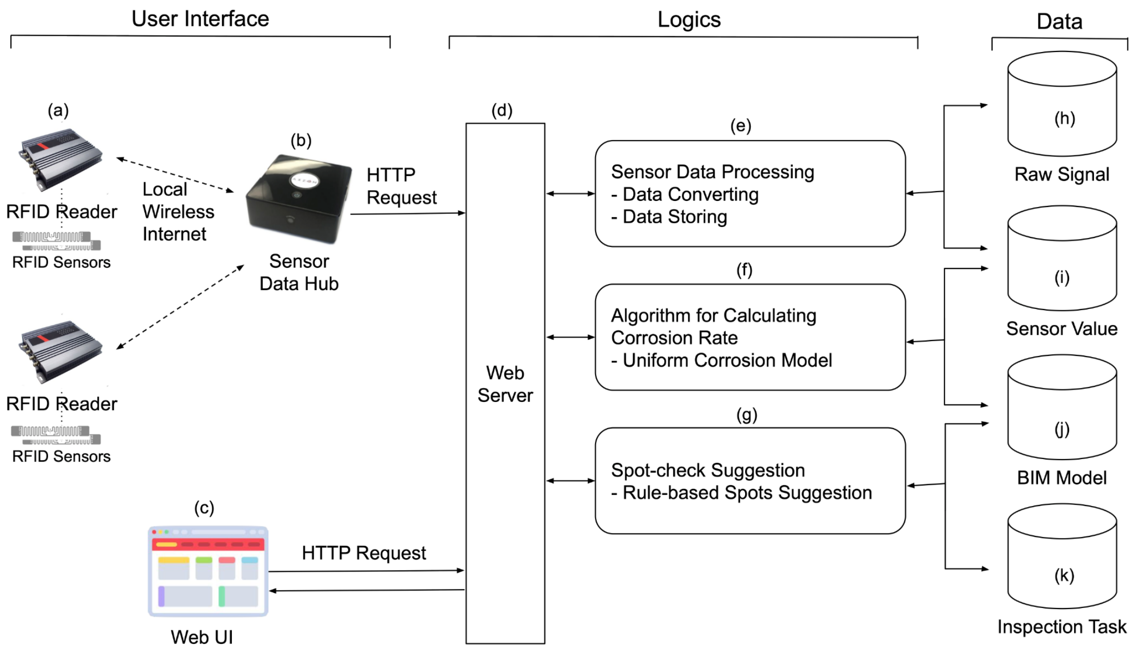


Figure 14. System architecture for predicting corrosion under insulation

4.3.5 Module 1: Data Collection

Each sensor has its own advantage and is dedicated to a specific environment. In general, passive RFID sensors which are battery-free and wireless are essential. Rather than using active sensors which need a power source inside, passive sensors do not need batteries of wiring for power. Therefore, the action of changing batteries is eliminated.

Because of this elegant mechanism, passive sensors are almost maintenance-free devices and designed for set-n-forget operation. It makes passive RFID sensors cost-effective by the reduction of maintenance fee. In order to collect applicable values from both temperature and moisture sensors on pipelines, a series of passive sensors provided by RFMicron, a sensing solution company, are considered.

For moisture sensors, three sensors are taken into consideration: RFM2100, RFM2110, and RFM2120 as shown in Figure 15. These sensors are dedicated for different working environments. Firstly, RFM2100 is dedicated for sensing environmental and material moisture, for example, monitoring moisture on food products, building and roofing materials, or moisture detection for corrosion prevention. It is configured to be sensitive to moisture and rain which results in relatively accurate to other moisture sensors. However, this sensor is not suitable for direct use on metallic surfaces due to the high interference with radio frequency. Second to all, RFM2110 detects in direct contact or liquid brought to the sensor through wicking tails. Because of this design, RFM2110 is configured to detect moisture when placed on metallic surfaces. Therefore, it could be deployed to the application of moisture detection in automotive vehicle assembly, aircraft maintenance or corrosion prevention programs. Lastly, RFM2120 are capable of detecting moisture similar to RFM2100. They are configured to be sensitive to moisture and rain, but only work on non-metallic surfaces. The only difference is that RFM2120 is sensitive to a slight change of moisture which mostly targets the medical applications. In brief, RFM2110 is chosen as the moisture sensor. The reason is that most pipelines on site are made of metal. It is essential to choose a metal-compatible sensor which could resist the interference of radio frequency. Besides, even though the sensor values may not be sensitive to a slight change of moisture, sensor values from RFM2110 suffice the need of corrosion prediction because only the scale of moisture is needed.

In terms of temperature sensors, three sensors are taken into consideration as well which are RFM3200, RFM3240, RFM3250 as shown in Figure 15. As the aforementioned discussion, the ability of working on metallic surfaces is essential. Therefore, only RFM3240 and RFM3250 are applicable for the proposed approach because RFM3200 is not configured to direct use on metal. On the other hand, both RFM3240 and RFM3250 can get exact values for temperature. The differences between these two sensors are the size of sensors, read range, and read angle. In order to decide a better fit to the practical use, detailed comparisons are conducted. First of all, in terms of the size of sensors, RFM3240 has larger size than RFM3250 by two times wider and five times higher as shown in Figure 16. Despite RFM3250 having a more compact build, both sizes of sensors are suitable for deployment on site. Regarding read range and angle, a lab test is conducted. Both sensors are attached on a pipeline to measure the maximum of read range and read angle. The results for these sensors are shown in Figure 17 and Figure 18. Specifically, RFM3240 has approximately 8 metres for its maximal read range and 30 degrees for its read angle; on the other hand, RFM3250 has approximately 1 metre for its maximal read range and 10 degrees for its read angle. It is indicated that RFM3240 has a better read range and read angle than RFM3250 which provides a possibility of minimal amount of sensors while deploying on site and reduces the initial cost of installation. In short, RFM3240 is chosen for temperature sensors because of its suitable size, better read range and angle compared to others.

Figure 15. Moisture and Temperature sensors: (a) RFM2100 - wireless moisture sensor (b) RFM2110 - wireless moisture sensor (c) RFM2120 - wireless moisture sensor (d) RFM3200 - wireless temperature sensor (e) RFM3240 - wireless temperature sensor (f) RFM3250 - wireless temperature sensor

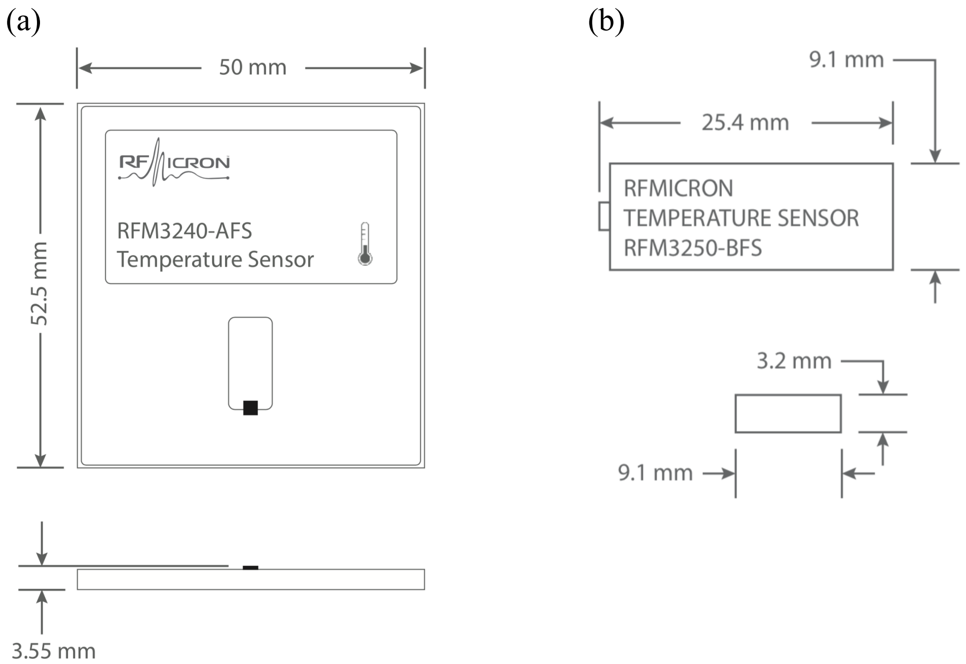
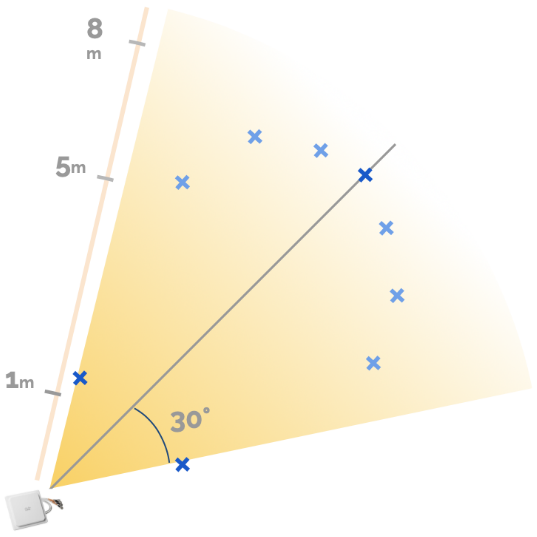
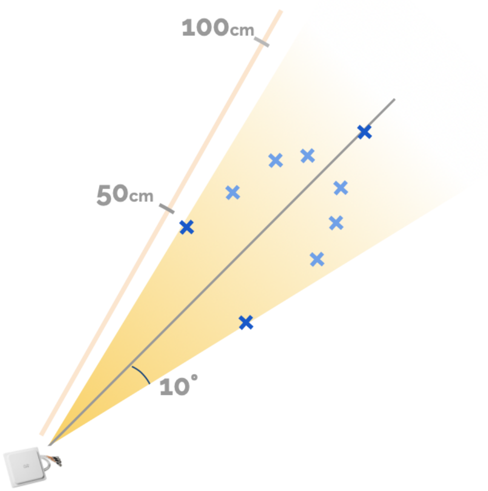


Figure 16. Size of temperature sensors: (a) RFM3240 - wireless temperature sensor (b) RFM3250 - wireless temperature sensor



	Maximum Distance (m)	Received Signal Strength Indicator (RSSI)
30°	1.29	6.0
20°	5.58	6.0
10°	7.00	7.0
5°	7.80	9.0
0°	8.10	9.0
-5°	7.61	8.0
-10°	6.97	8.0
-20°	5.05	7.0
-30°	1.04	6.0

Figure 17. Read range and read angle for RFM3240



	Maximum Distance (m)	Received Signal Strength Indicator (RSSI)
10°	0.49	6.0
7.5°	0.68	6.0
5°	0.77	7.0
2.5°	0.80	9.0
0°	1.02	9.0
-2.5°	0.81	8.0
-5°	0.78	8.0
-7.5°	0.64	7.0
-10°	0.54	6.0

Figure 18. Read range and read angle for RFM3250

Fixed reader AR52 RFM5008 manufactured by Nordic ID has been chosen. The main reason why this reader is chosen is the reader's ability to automatically detect the sensor data over a certain period of time. Using AR52 RFM5008 along with the antenna, data can be updated every thirty seconds and stored into the database which can help in easy extraction and input into the BIM system. Apart from the reader, a customised data hub has also been used which is a raspberry pi system to be an intermediary of the reader and server aimed at storing data (Figure 19). Data hub can assist in converting the raw data into meaningful information and display them onto the customised dashboard as Figure 20.

(a) (b)

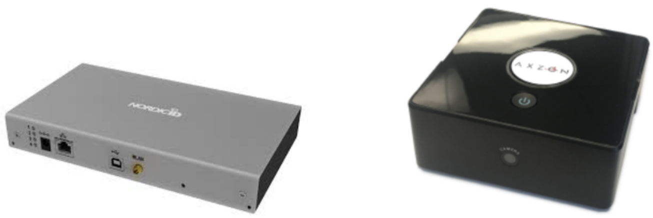


Figure 19. (a) Fixed reader AR52 RFM5008 (b) data hub

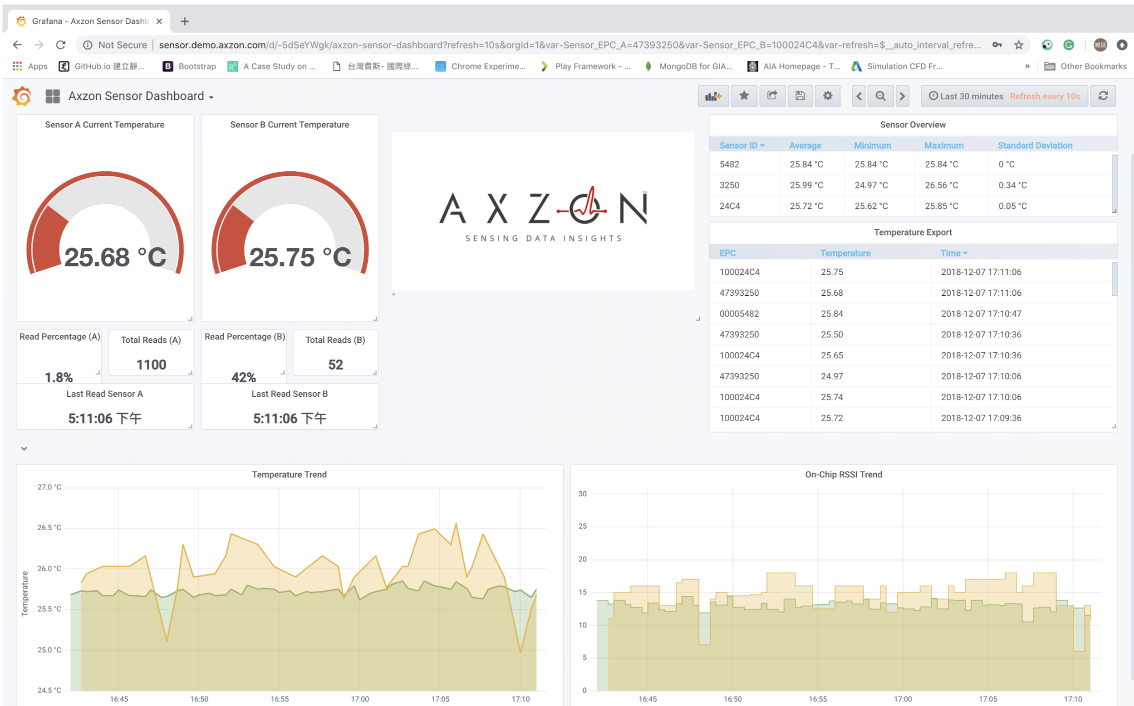


Figure 20. Real-time sensor values on the AXZON dashboard

To insert the sensor data into the BIM model for visualisation, system architecture shown in Figure 14 should be explained in more details. While RFID readers monitor RFID sensors (Figure 14a) on site, the sensor data is continuously collected by sensor data hub (Figure 14b). Then, HTTP requests with sensor data are sent to the web server (Figure 14d) to process the data input. The data are converted by the logics of sensor data processing (Figure 14e) and stored in raw signal database (Figure 14h) and sensor value database (Figure 14i) for further usages. Because all RFID sensors are pre-coded with the element identification in the BIM model, the sensor values could be easily mapped to BIM elements when needed. Once a user accesses the web UI (Figure 14c), the system retrieves the model from BIM model database (Figure 14j) and the sensor data from sensor value database (Figure 14i) to display both static and dynamic data in the system. In brief, it is shown that the data hub acts as a bridge to stream data from numerous readers on site to the cloud system. With these abundance of sensor data, sensor data visualisation and corrosion predictions could be realised.

When a corrosion prediction function is triggered from the web UI (Figure 14c), the system retrieves sensor values from sensor value database (Figure 14i) to get the inputs for the algorithm of corrosion prediction. The predicting process (Figure 14f) then calculates estimated corrosion depth at a given time period. As a result, the estimation of corroded depth is embedded in element properties in the BIM model. Besides, these values could be colour-coded on the BIM model to have a better understanding of the corrosion prediction on a larger scale.

4.3.6 Module 2: Data Analysis

Whenever clicking on a pipeline element from the BIM model, value in element's attributes would update. Apart from some static information received from the BIM model itself, some extra sensor information is attempted to be embedded in each BIM element from the system. A property group called "Sensor Data" is created to accommodate our sensor data measured, such as "Moisture Calibration", "Moisture Tracking", "Temperature Calibration", "Temperature Tracking", "Moisture Delta", "Corrosion Rate", "Prediction Time Duration" and "Corrosion Prediction" as shown in Figure 21. Among the embedded properties, corrosion rate is calculated by the algorithm and the prediction time duration is from user inputs on web UI. In short, the example shows the mechanism of streaming sensor data to elements in the BIM model and integrated with the proposed system.

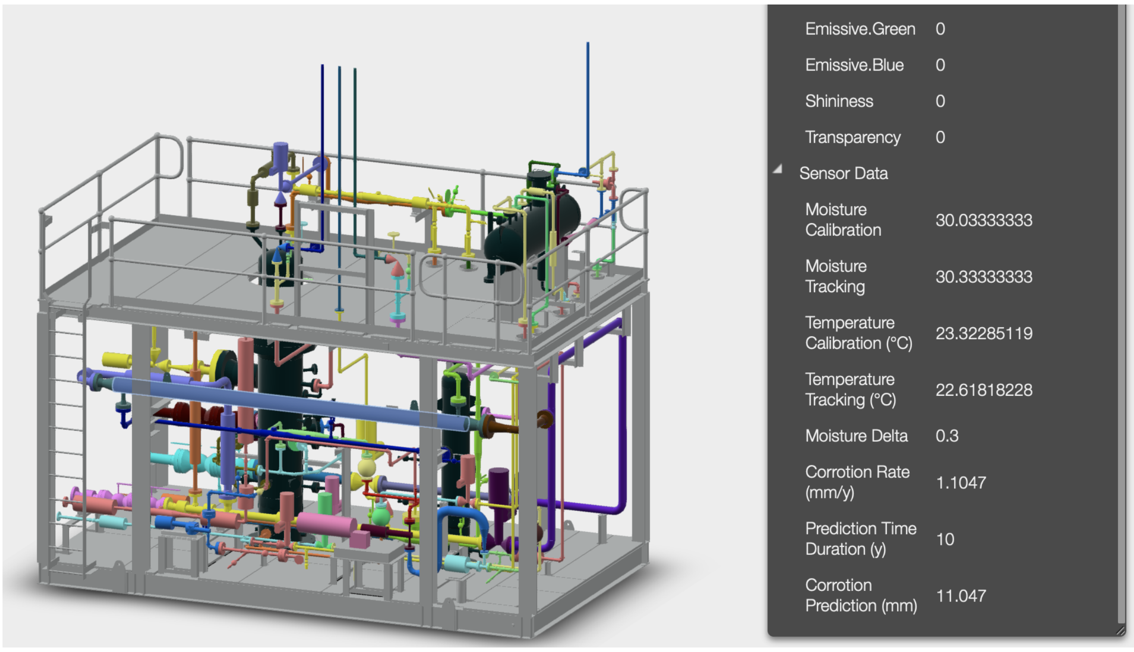


Figure 21. Property Panel of a section of pipeline in web-based BIM model viewer

To apply the dynamic and static data to the mathematical model for corrosion prediction, the chemical interactions of the corrosion process was investigated. Specifically, as the emergence of oil and gas normally accompanies by water and various amounts of acid gases, such as carbon dioxide, CO_2, it affects the integrity of mild steel which is often used in construction material in the oil and gas industry. To understand the CO_2 corrosion of mild steel, this research integrates with an entry level corrosion simulation and prediction model which mathematically illustrates the electrochemical process of the CO_2 corrosion. To be specific, a uniform corrosion is assumed as the corrosion prediction model.

The reason for the selection is that there are some factors which affect the reaction during the corrosion, yet not easily integrated with sensors. For example, the dissolution of iron is pH dependent. Namely, the more iron is dissolved, the faster corrosion is reacted which results in higher corrosion rate. However, there may be difficulties for acquiring passive sensors to monitor pH scale due to the lack of power on passive sensors. This situation may be fixed once the sensing technology comes up with energy-efficient sensors. Until then, selecting a simplified corrosion model which assumes some factors as constants could be an alternative. It may influence the accuracy of corrosion prediction, but still be applicable in practical usages.

Mild steel is chosen as standard pipe material in the uniform corrosion. The pipelines are corroded by acid gases such as H_2CO_3 which is generated from carbon dioxide. In these reactions, two main elements for corrosion are carbon dioxide, CO_2, and water, H_2O. The overall reaction of the electrochemical process for carbon steel is shown in Equation 1.

$$Fe + CO_2 + H_2O \rightarrow FeCO_3 + H_2 \qquad \text{Equation 1}$$

To look into the details of electrochemical reactions of Equation 1, the electrochemical dissolution of iron in water is the dominant anodic reaction in corrosion which is shown as Equation 2. This reaction is pH dependent on acidic solutions which means the lower the pH scale is, the faster the iron dissolution happens which results in affecting the overall reaction. However, because of the assumptions from the selected corrosion model, pH scale of corrosion is assumed as neutral which means the pH scale will not affect the corrosion.

$Fe \rightarrow Fe^{2+} + 2e^{-}$ Equation 2

The CO_2 gas in the environment is soluble in water and makes carbonic acid, H_2CO_3. The dissolution of carbon dioxide is expressed as Equation 3. This reaction is affected by temperature and moisture. Namely, the solubility of carbon dioxide decreases while the temperature increases which increases the reaction rate to acidic gases, H_2CO_3. This carbonic acid from Equation 3 further dissociates in water to produce hydronium which is shown in Equation 4 and Equation 5. Apart from the temperature factor, moisture could affect the reaction rate in Equation 3 as well. The carbon dioxide could only form carbonic acid, H_2CO_3, with adequate amounts of moisture, H_2O. In other words, if there is not enough moisture, carbon dioxide in Equation 3 stays in the form itself and produces no acidic gas which stops the reaction of corrosion. In short, both temperature and moisture are two important factors when it comes to corrosion rate.

$CO_2 + H_2O \Leftrightarrow H_2CO_3$ Equation 3

$H_2CO_3 \Leftrightarrow H^{+} + HCO_3^{-}$ Equation 4

$HCO_3^{-} \Leftrightarrow H^{+} + CO_3^{2-}$ Equation 5

By calculating the reaction rates from each aforementioned dissolution, the corrosion rate for pipelines could be identified. There are two variables taken into consideration:

temperature and moisture. Temperature values from sensors serve as inputs (T_c) in the following equations to calculate the reaction rate for each electrochemical process. On the other hand, moisture values serve as the determination whether the electrochemical process could start. As a result, corrosion rate on each pipeline could be calculated independently based on the attached temperature and moisture sensors.

These corroded reactions are a series of charge transfers. To specify the charge transfer for the aforementioned reactions, the overall corrosion potential (i_c) and current density (i_a) can be written as Equation 6. By using the Tafel equation (McCafferty, 2005), electrochemical kinetics for the electrochemical reactions could be calculated. Each corrosion potential and current density in Equation 6 can be formulated, as shown in Equation 7, Equation 10, Equation 14, and Equation 18.

$$i_{c(H^+)} + i_{c(H_2CO_3)} + i_{c(H_2O)} = i_{a(Fe)} = i_{corr} \qquad \text{Equation 6}$$

Equation 7 shows the calculation of current density of iron. Regarding symbols, i_O is the exchange current density of dissolution. E_{corr} is corrosion potential (V). $E_{rev(Fe)}$ is reversible potential of dissolution, $E_{rev(Fe)} = -\ 0.488\ V$. $b_{a(Fe)}$ is the anodic Tafel slope for Fe dissolution.

$$i_{a(Fe)} = i_{O(Fe)} 10^{(E_{corr} - E_{rev(Fe)})/b_{a(Fe)}} \qquad \text{Equation 7}$$

The exchange current density, $i_{O(Fe)}$, and the anodic Tafel slope, $b_{a(Fe)}$, are functions relative to temperature. Equation 8 and Equation 9 explain the functions where $i^{ref}_{O(Fe)}$ is reference exchange current density of Fe oxidation, $i^{ref}_{O(Fe)} = 1\ Am^{-2}$, ΔH_{Fe} is activation enthalpy, $\Delta H_{Fe} = 50\, kJ\, mol^{-1}$, R is universal gas constant, $R = 8.314\, J\, mol^{-1}K^{-1}$, T_c is temperature (℃), $T_{c,ref}$ is reference temperature, $T_{c,ref} = 25$ ℃, F is Faraday's constant, $F = 96485\, C\, mol_e^{-1}$.

$$i_{O(Fe)} = i_{O(Fe)}^{ref} exp(\frac{-\Delta\Delta H_{Fe}}{R}(\frac{1}{T_c+273.15} - \frac{1}{T_{c,ref}+273.15}))$$ Equation 8

$$b_{a(Fe)} = \frac{2.303R(T_c+273.15)}{1.5F}$$ Equation 9

Equation 10 illustrates the calculation of current potential of hydronium ions. In terms of symbols, $E_{rev(H^+)}$ is reversible potential for H^+ ion reduction (V). $b_{c(H^+)}$ is cathodic Tafel slope for H^+ iron reduction (V). Because hydronium ion is reversible as shown in Equation 4 and Equation 5, $E_{rev(H^+)}$ is calculated in Equation 13. Besides, Equation 11, Equation 12, and Equation 13 are affected by temperature.

$$i_{c(H^+)} = i_{O(H+)} 10^{(E_{corr} - E_{rev(H+)})/b_{c(H+)}}$$ Equation 10

$$i_{O(H^+)} = i_{O(H^+)}^{ref} exp(\frac{-\Delta\Delta\Delta H_{(H^+)}}{R}(\frac{1}{T_c+273.15} - \frac{1}{T_{c,ref}+273.15}))$$ Equation 11

$$b_{c(H^+)} = \frac{2.303R(T_c+273.15)}{0.5F}$$ Equation 12

$$E_{rev(H^+)} = -\frac{2.303R(T_c+273.15)}{F} pH$$ Equation 13

Equation 14 calculates the current potential of carbonic acid. As for the symbols, $E_{rev(H_2CO_3)}$ is reversible potential for H_2CO_3 reduction (V). $b_{c(H_2CO_3)}$ is cathodic Tafel slope for H_2CO_3 reduction (V). Since the reductions of H_2CO_3 and H^+ are equivalent, $E_{rev(H_2CO_3)}$ is same as $E_{rev(H^+)}$ shown in Equation 17. In addition, Equation 15, Equation 16, and Equation 17 are affected by temperature.

$$i_{c(H_2CO_3)} = i_{O(H_2CO_3)} 10^{(-E_{corr} - E_{rev(H_2CO_3)})/b_{c(H_2CO_3)}} \quad \text{Equation 14}$$

$$i_{O(H_2CO_3)} = i^{ref}_{O(H_2CO_3)} exp(\frac{-\Delta H_{(H_2CO_3)}}{R}(\frac{1}{T_c+273.15} - \frac{1}{T_{c,ref}+273.15})) \quad \text{Equation 15}$$

$$b_{c(H_2CO_3)} = \frac{2.303R(T_c+273.15)}{0.5F} \quad \text{Equation 16}$$

$$E_{rev(H_2CO_3)} =- \frac{2.303R(T_c+273.15)}{F}pH \quad \text{Equation 17}$$

Equation 18 identifies the current potential of water. With regard to symbols, $E_{rev(H_2O)}$ is reversible potential for H_2O reduction ($A\,m^{-2}$). $b_{c(H_2O)}$ is cathodic Tafel slope for H_2O reduction (V). Because the reductions of H_2O and H^+ are equivalent, $E_{rev(H_2O)}$ is same as $E_{rev(H^+)}$ shown in Equation 21. In addition, Equation 19, Equation 20, and Equation 21 are affected by temperature.

$$i_{c(H_2O)} = i_{O(H_2O)} 10^{-(E_{corr} - E_{rev(H_2O)})/b_{c(H_2O)}} \quad \text{Equation 18}$$

$$i_{O(H_2O)} = i^{ref}_{O(H_2O)} exp(\frac{-\Delta H_{(H_2O)}}{R}(\frac{1}{T_c+273.15} - \frac{1}{T_{c,ref}+273.15})) \quad \text{Equation 19}$$

$$b_{c(H_2O)} = \frac{2.303R(T_c+273.15)}{0.5F} \quad \text{Equation 20}$$

$$E_{rev(H_2O)} = -\frac{2.303R(T_c+273.15)}{F}pH \qquad \text{Equation 21}$$

By substituting the expressions in Equation 6 to Equation 21, the only unknown corrosion potential, E_{corr}, can be solved. The value of E_{corr} is returned to the Equation 6. Then, the reaction of corrosion, i_{corr}, can be solved. Once i_{corr} is solved in Equation 6, the corrosion rate (CR) can be further calculated. Finally, the corrosion rate is computed by Faraday's law (Cottis, B., Graham, M.J., Lindsay, R., Lyon, S.B., Richardson, T., Scantlebury, D., Stott, H., 2010) as shown in Equation 22 where M is the molecular mass, ρ is the density, n is the number of electrons and F is the Faraday's constant. If the unit amperes per square meters is used for the corrosion current density, i_{corr}, the corrosion rate expressed in millimeter per year is computed as: $CR = 1.155\, i_{corr}$.

$$CR\ (mm\ per\ year) = \frac{i_{corr} M_{Fe}}{\rho_{Fe}\, n\ Equation\ 23F} \qquad \text{Equation 22}$$

Inputs for the calculation of corrosion rate can be extracted from BIM models due to the well-arranged properties within each element. By integrating sensor values and static properties in the BIM model, these inputs can easily fit into the corrosion rate calculation as shown in Figure 22. Although the assumptions may be different from each corrosion model and result in different inputs, Figure 22 lists the potential properties for corrosion rate calculation.

Property	Value
host Element GUID	d824b4b6-761c-466c-b331-01a4799fca5d
Pipe Thickness	0.007
Pipe Material	Copper
Pipe Size	54 mmø
Pipe Length	3.937
Pipe Year	2.000
Operating Tempe...	10 °C
Coating Type	Copper
Insulation Type	None
Oxygen	5.000
Humidity	33.000

Figure 22. Inputs for corrosion model from BIM model

4.3.7 Module 3: Application

In order to visualise sensor values or prediction results, it is essential to acquire BIM applications which enables users to visualise 3D BIM models and develop user-defined extensions to achieve specific functions. Forge is one of the aforementioned applications developed by Autodesk company. It encompasses all the functions needed in a visualisation tool and the main difference of this platform from others is its web-based characteristic. Through any internet browser, users can view the 3D BIM model colour-coded with sensor values and have the real-time corrosion prediction result for each pipeline displayed in the element's property panel. Figure 21 shows an example of a web-based BIM model viewer.

The approach assists users in efficiently identifying which pipeline suffers from heavy corrosion and needs to be replaced. A web-based system powered by Forge is developed to integrate the sensors, mathematical model, and BIM models. To visualise the results in the system, three different thresholds have been set for moisture, temperature and corrosion depth respectively.

Once the sensor data already is imported into Forge, a corresponding colour would also be given to each pipeline element in accordance with the thresholds. For example, after clicking on the moisture visualisation button, the black colour would be given to the pipeline with moisture delta value below 0.01mm, and the blue colour represents pipeline with moisture delta value over 0.01mm as shown in Figure 23.

As for the corrosion visualisation, the same mechanism is used, yet different colours are chosen. When the corrosion prediction is triggered, the application retrieves the latest sensor values on each pipeline for the algorithm of corrosion prediction. Then, the algorithm calculates the corrosion rate, which unit is millimetre per year, then embedded the value on each element of pipelines. With the corrosion rate of each pipeline, the predictive depth of corrosion can be calculated which considers prediction time duration, corrosion rate, and safety factor all together. Among the inputs of the calculating corrosion depth, prediction time duration is a user input which specifies the target date of corrosion prediction. As shown in Figure 24, users can pick up prediction time through the interface. After selecting the time, the attribute "Prediction Time" of each element will automatically update. As the corrosion rate for each element has been calculated in advance, the corrosion prediction depth would also update and be embedded in elements.

Predictive corrosion depth is colour-coded on pipelines to identify corrosion level on site. The scale of colour coding is customisable to accommodate various site conditions. Generally, values of the scales could be set along with the inspection needs. In this case, as Figure 25 shown, grey colour is configured as normal which corrosive depth is less than 3 mm; ivory colour is configured as the “may inspect” pipelines which corrosive depth is between 3 to 5 mm; on the other hand, the dark red colour is configured as the “must inspect” pipelines which corrosive depth is over 5 mm. In result, the pipeline with dark red colour means replacement is needed severely whereas the grey pipeline indicates no attention is needed on that particular item. These colour coding intuitively assist users in understanding which pipeline needs detailed inspection.

In some cases, target pipelines for inspection may not be easily identified because the corrosion depth of these pipelines are all categorised into the same level which results in the same colour on the BIM model. In this situation, the prediction time of attributes should be modified to find a suitable value for distinguishing severely corroded pipelines from slightly corroded pipelines. As an alternative, a rough area with corroded pipelines could be identified through the colour-coded BIM model. Then, inspectors could compare among sensor values of the pipelines and locate the possible corroded pipelines by their site experience.

In short, traditionally, an inspection takes place while an inspector assumes that the pipeline in some particular area is heavily corroded based mainly on site experience or some laboratory experiment. However, with the proposed approach, inspectors can take advantage of the corrosion value embedded in each element and the colour-coded visualisation to make decisions as to where to inspect. It is not necessary to find the exact corrosion depth of every pipeline, at least the BIM model with colour coding function can assist in identifying the trend of corrosion which can be auxiliary information for the inspector to consider.

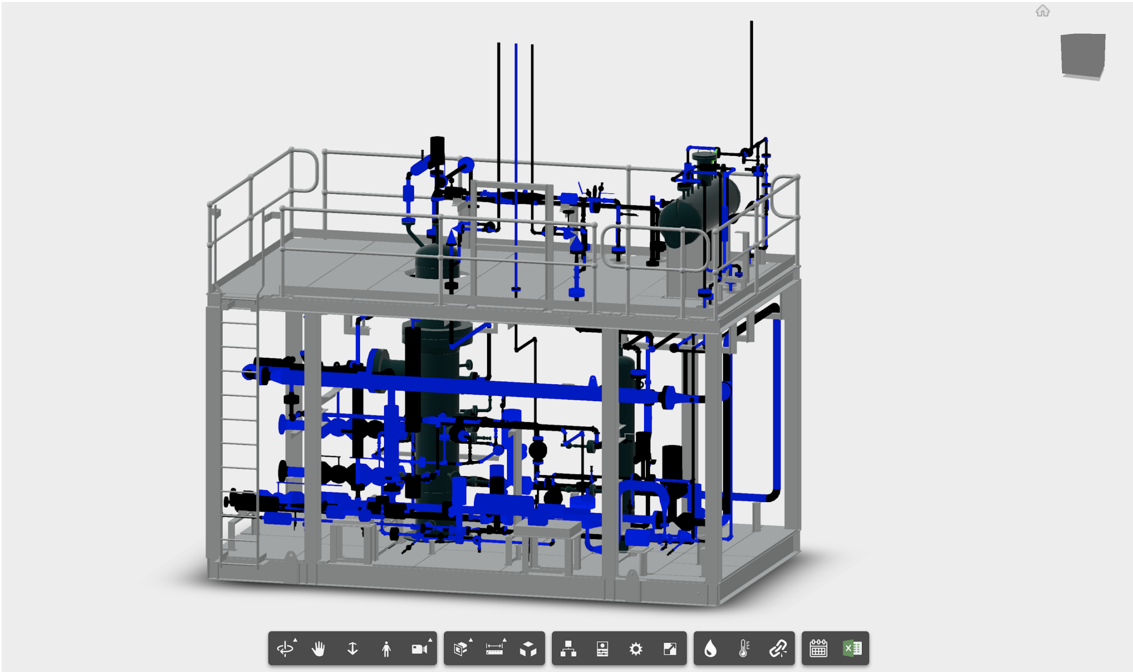


Figure 23. Colour coding for moisture values on pipelines

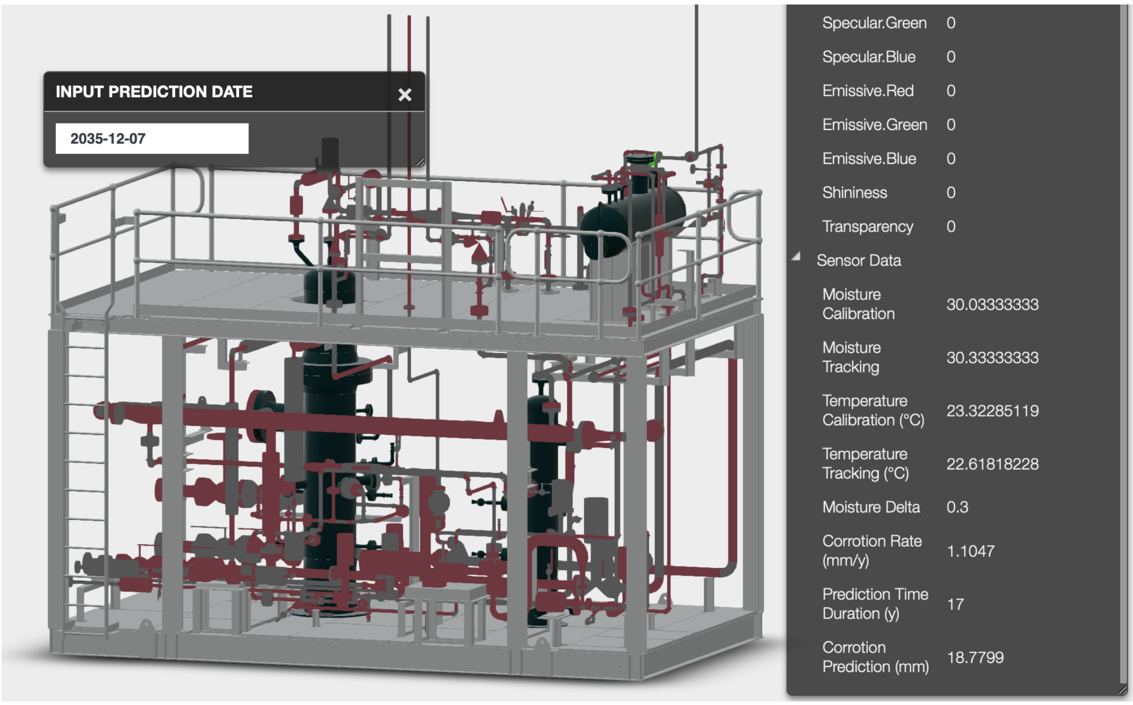


Figure 24. Selecting a time period for corrosion prediction

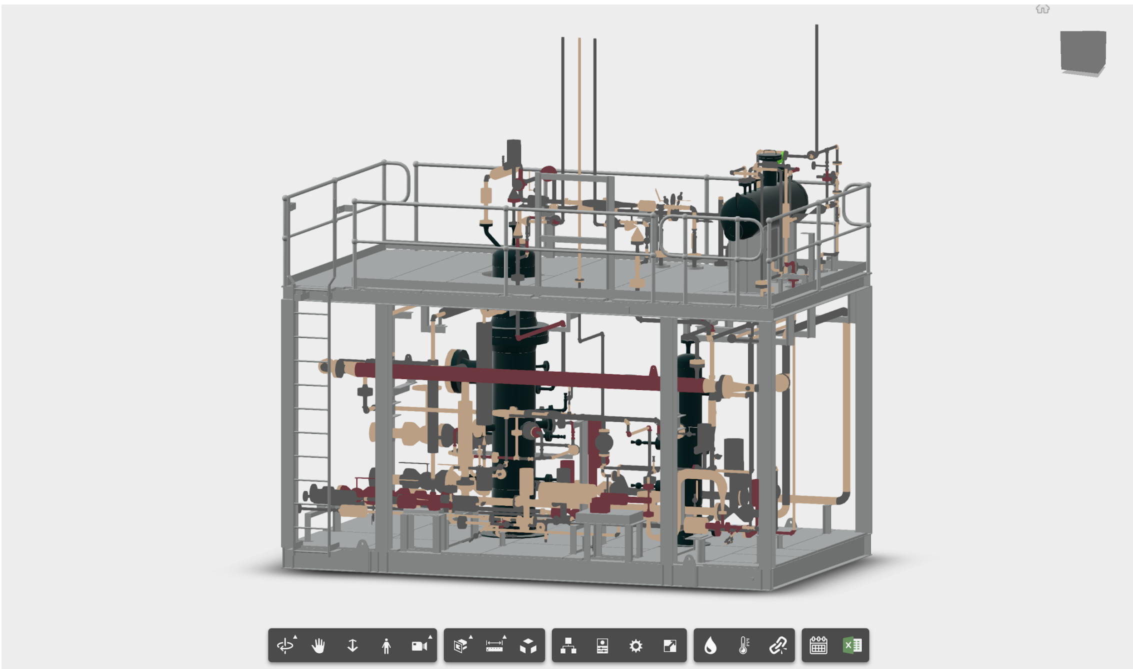


Figure 25. Colour coding for corrosion depth on pipelines

4.4 Discussions

This chapter proposed a framework which leverages the BIM and field sensing technologies to assist the decision making process. A novel approach following the framework was implemented to predict corrosion under insulation. Namely, sensing technology and the mathematical model of corrosion prediction are implemented into a BIM-based system. The sensor values and analytic results of corrosion prediction were visualised on BIM models. As a result, inspection areas could be decided mainly by the data rather than experience or instincts. Besides, the period of pausing production could be reduced because there is less time demand for spot-checking the status of corrosion under insulation. A demonstrative case is implemented to validate the practicality of the proposed framework.

Chapter 5: Designing BIM-enabled Work Packaging for Strengthening Information Linkages in Complex Projects

5.1 Introduction

Project information is scattered because there are multiple sources of information which come from different stakeholders across the project lifecycle. Besides, every stakeholder may have different data types and formats without a uniform data structure. Therefore, when the decision making process starts, it is challenging to extract and integrate all the relative information from the project data pool. For instance, BIM models, drawings, check lists, contracts are different from one another regarding the data types and formats. All the data is stored in a central data pool in a folder structure. When the decision makers need the information, they scan through the folders and collect all the relative files. If some data is not picked throughout the project lifecycle, the data is wasted as it does not add any values to the project. The information flow is interrupted as well. Therefore, Building the connection between data is essential for a smooth information flow as all the relative information can be extracted all at once when needed.

Chapter 5 develops a BIM-enabled work packaging approach for strengthening information linkages in complex projects (Research Objective 2). Specifically, the approach was designed based on the use of BIM technology to strengthen connections among project data. By linking the data in different levels, geometric and non-geometric information can be properly interconnected. The designed approach includes four major modules: a data preparation module, work package planning and generation module, work package linking module, and work package updating module. Furthermore, a process model was designed to present the application of the work packaging method in current practice. In this chapter, the fundamental elements of information were identified. Then, the mechanisms for linking project data were elaborated level by level. Subsequently, a framework of BIM-enabled work packaging was proposed to provide an approach for strengthening information linkages in complex projects. The system architecture was designed to validate the feasibility of the proposed approach, and a pilot study was presented to demonstrate the outcomes of interconnected project data.

5.2 A Framework of Strengthening Linkages across Work Packages

The framework of the proposed BIM-enabled work packaging approach is illustrated in Figure 26, which includes four main modules: data preparation, work package planning and generation, work package linking, and work package updating. Each module is explained in detail in the following subsections.

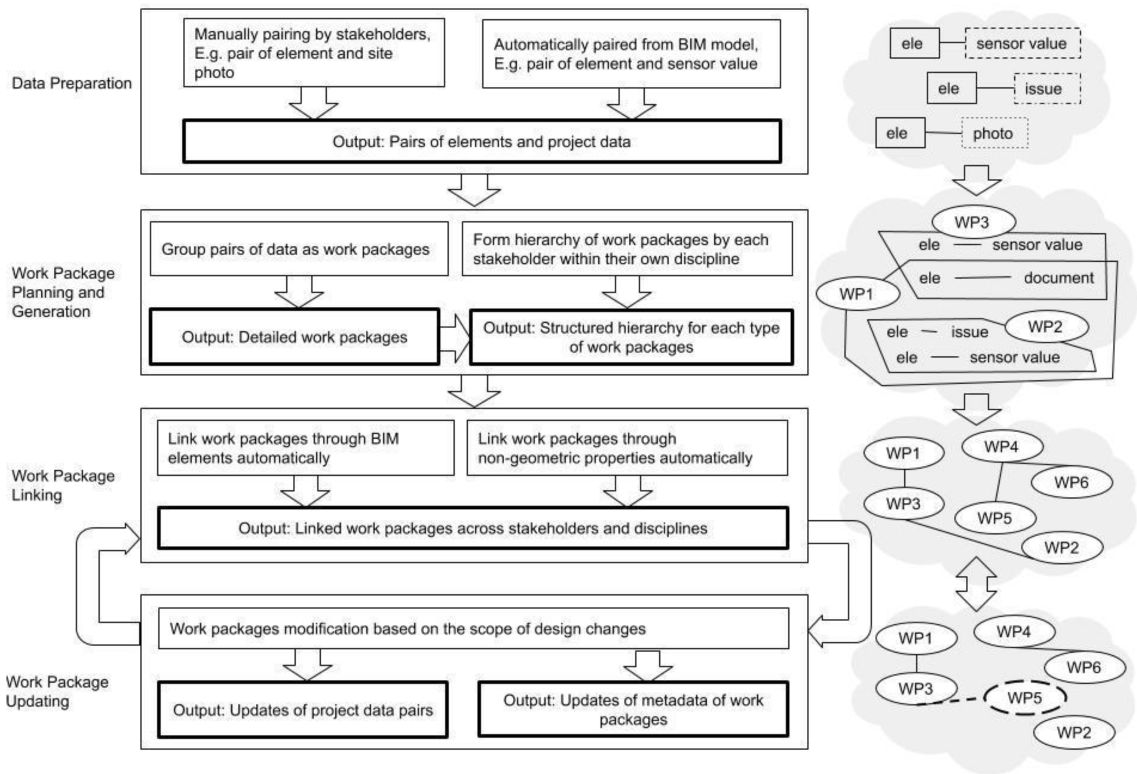


Figure 26. Framework of the proposed BIM-enabled work packaging

5.2.1 Module 1: Data Preparation

The main purpose of this module is to index project data using BIM, which provides a common data format for work packaging. In particular, scattered data in the project data pool are linked to BIM elements. This is a many-to-many relationship. At this stage, non-geometric data such as documents, photos, or sensor values should be linked to BIM elements. The element pairing process could be conducted either automatically or manually. When automatically pairing, data and BIM elements could be paired when the data is generated by the system. For example, sensors may be installed on site to monitor the project. Therefore, the sensor values could be automatically paired to their host in the BIM model. Another example for automatic pairing is reports or issues generated by the system. For instance, clash detection is an important process to assure a conflict-free project; here, clash detection could be done by the algorithm. Reports and issues could be created afterwards to highlight the clashes. In this scenario, elements are paired to the reports and issues automatically. When manually pairing, stakeholders could specify the related elements for those data that cannot be automatically paired, such as site photos. Although the manually pairing process could be tedious, it ensures that most of the data is paired, which helps increase the quantity and quality while grouping and retrieving data at the following steps.

In fact, abundant research studies propose approaches for both automatically and manually linking BIM elements to project data. For example, an integrated platform for facilities management is designed by integrating BIM into a sensor-based approach for fault detection and alerting malfunction in the operational phase (Valinejadshoubi et al., 2021). Multiple sensors are integrated with BIM and then visualized in a cloud-based system. The sensor data is automatically linked to the BIM elements by a visual programming tool which also extracts and sends sensor data to the system achieving an effective Internet of Things (IoT) approach for maintenance. Besides, the solution helps facility managers in taking timely actions in the event of an emergency or malfunction. Another research demonstrated that the automatically linked sensor data could be further adopted for the corrosion prediction model in the plant site operation (Yuan Hao Tsai et al., 2019). Specifically, the identification of the BIM element is embedded in the sensor to fulfill the automatic linking. Then, the sensor data is streamlined to the prediction model as inputs for corrosion prediction analysis. Both sensor values and prediction results are visualized on the BIM model to provide an intuitive interface for inspectors to sketch the maintenance plan. On the other hand, in terms of the manually linking of data and BIM elements, an international airport project was investigated (Kula & Ergen, 2021). Due to the large-scale facility of the international airport, the process of integrating BIM and FM involved multiple practitioners to collect, identify, and integrate the data. The specifications, warranties, and the BIM models were uploaded to the platform separately. Afterwards, dedicated practitioners associate the documents with BIM elements. In short, linking project data with BIM objects is important and has been implemented into both academic and industrial projects with different mechanisms and workflows.

Many research studies focus on linking project information to BIM objects for information management, yet the linkages among the paired information, e.g. linkages of work packages, have not been paid great attention to. In pace with the growth of the numbers of work packages in the project data pool, a linking mechanism should be established to enhance the quality while retrieving work packages. Namely, similar scope of work packages should be retrieved together to reduce the possibility of missing information. To achieve the work package linking, paired information in the work package should serve not only the details of the work, but also the identity among work packages for finding similar work packages. Therefore, this research puts more emphasis on the work package linking over the linking between BIM elements and project data because the work package linking is scarce yet essential to the proposed approach. The mechanism of work package linking is elaborated in the work package linking module.

5.2.2 Module 2: Work Package Planning and Generation

The main purpose of this module is to consider stakeholders planning their work and utilizing the data from the data preparation module to generate a series of work packages. Specifically, a series of work packages are produced from each type of stakeholders. These work packages store project data in three aspects: elements, metadata, and details of the work package. In particular, elements record the related BIM elements of the work, the metadata stores the basic information to describe the work package, and lastly, the details store the non-geometric data of the work within the project data pool to specify the task. Therefore, each work package meaningfully groups project data to express and elaborate construction works.

At the beginning of the project (Figure 27a), designers sketch their preliminary design and add the design information to the engineering work packages (EWPs). BIM elements, layout, documents, or detailed requirements may be added to the EWPs to assist in the refinement of the design. During the process, procurement work packages (PWPs) may be created for equipment, services, or supplies for the following procurements. As the procurements may be carried out by any stakeholders, separating procurement information as an individual work package could help facilitate the procurement process. Once the design is mature and ready for reviewing and delivering, contractors engage in working on the plan for the construction stage.

Once contractors receive the notification from designers (Figure 27b), they formulate the construction plan as construction work packages (CWPs) by leveraging the engineering and supply chain information from EWPs and PWPs. The contractor could inventory the manpower, resources, or permits for the tasks in the CWPs. Once the requirements listed in the CWP are checked, the CWP is ready to issue for construction. This process assures all tasks are well-planned before construction and ready for subcontractors to finalize the details. Additionally, if the contractor were responsible for the procurement, the contractor would be asked to update the corresponding PWP and link it to the corresponding CWPs to maintain the information integrity of work packages.

Subcontractors obtain the construction information from CWPs assigned by contractors (Figure 27c). Then, they draft their execution plan as installation work packages (IWPs) for the specific tasks related to the assigned CWPs. It is worth noting that the scope of one CWP could cover multiple scopes of IWPs. This is because one CWP may be conducted by several subcontractors, and multiple IWPs may link to the same CWP. Furthermore, once each subcontractor completes their work and updates the properties in the IWP, contractors could check the progress from their CWPs due to the linkages between the CWPs and IWPs.

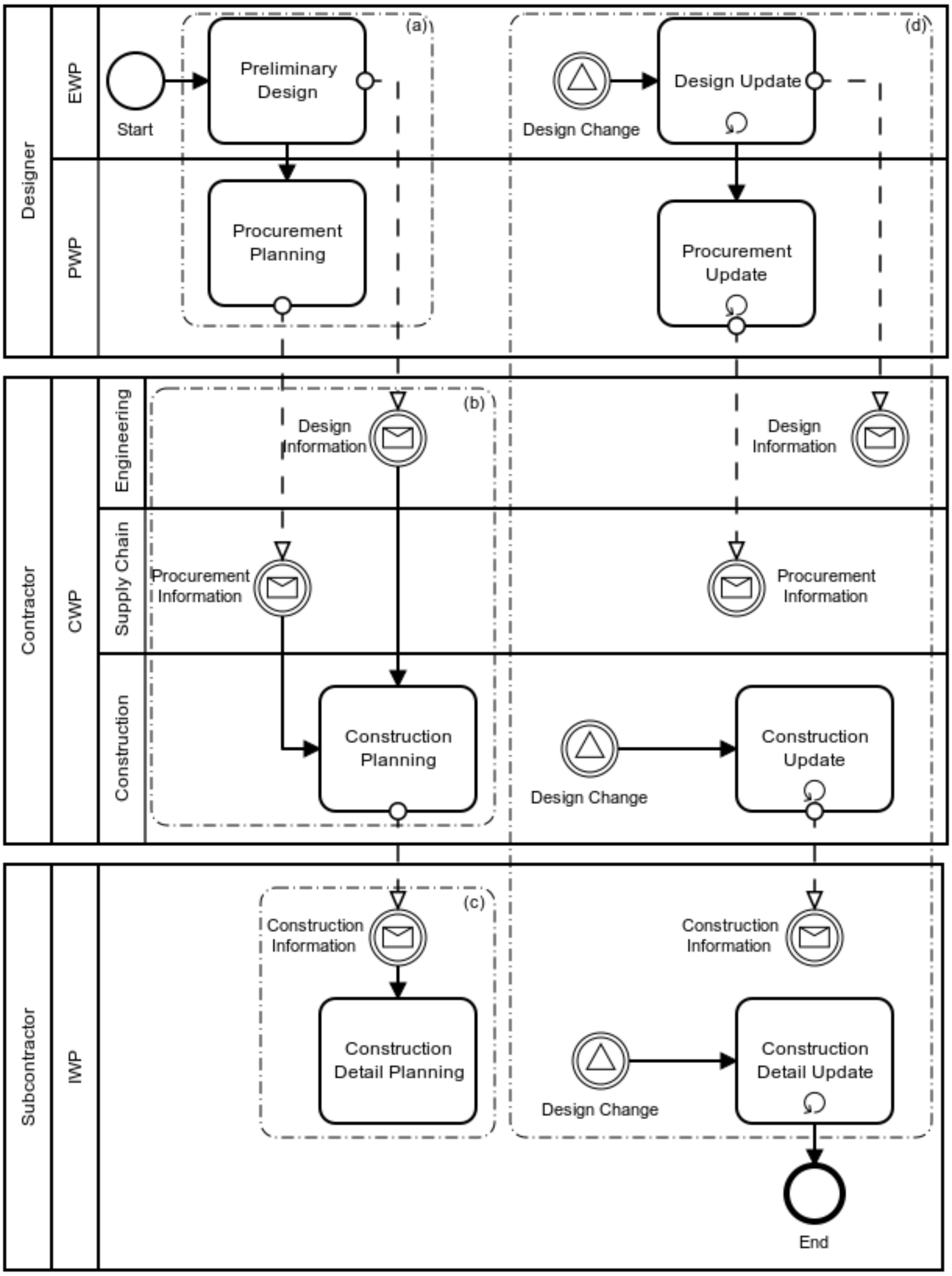


Figure 27. Process modelling of the work package planning for stakeholders

5.2.3 Module 3: Work Package Linking

The main purpose of this module is to link work packages generated by all stakeholders through geometric and non-geometric relationships among the work packages. When work packages are shared to the project data pool, they could be automatically linked by leveraging the properties from the work package planning and generation module. Generally, the work packages could be linked by geometric and non-geometric properties. In terms of the linking of geometric properties, if the work packages refer to the same group of elements, this indicates that multiple stakeholders or disciplines are tasked with the same design scope. Therefore, these work packages should be linked to avoid possible spatial or time conflicts during the construction stage. As to the linking of non-geometric properties, work packages may have similar constraints, e.g. high temperature, high wind speed, or high humidity, which have impacts on the productivity of the project. By leveraging the linkages from the non-geometric properties of work packages, site managers could prepare for these unexpected situations with less information loss.

Due to the similar form of work packages across project members, the work packages from different stakeholders could be shared to the project data pool and refer to each other (Figure 28). Among all linkage types, overlapped target elements, same constraints, sequential works, and hierarchy related work packages are the most common scenarios for adding linkages to work packages. First, when two or more contractors assign the same BIM elements to their work package, these work packages should geometrically link together due to the possible interferences in their construction periods, sequences, or conflicts. Second, there are various types of constraints for determining the sequence of the works as well, such as working temperature or humidity. If work packages have the same constraints, these work packages should be linked together to understand the scale of the impacts under the imposed constraints. Third, work packages could be linked chronologically to identify the sequences of the work packages. This also provides the information for the site manager for the previous and next tasks of the current work package. Finally, stakeholders follow the WBS to break down the construction activities into manageable sizes as a series of work packages. These form a hierarchy of work packages. By linking the work packages according to the hierarchy, the relationship among the work packages can be clearly shown in a global view. In this manner of linkages, project members can maintain the flexibility of information management within the team while simultaneously maximizing the information sharing.

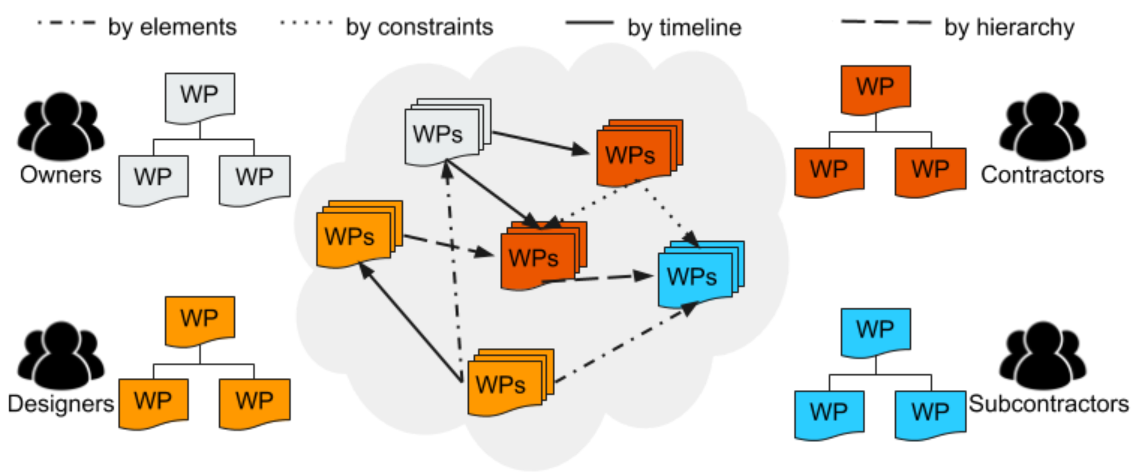


Figure 28. The information management concept for the project data pool

Apart from building linkages directly through properties in work packages, correlation of the work packages could be further analyzed to strengthen linkages among work packages. In fact, the calculation of correlation coefficient is widely adopted by recommendation engines in electronic commerce to analyze the behavior of customers for predicting preferences. For example, as shown in Figure 29, providers from video streaming service collect users' ratings of the shows. By analyzing the correlation between each user and their favorite shows, we can identify users with similar tastes of the shows. Therefore, when a new show is liked by one user, it could be recommended to other similar users.

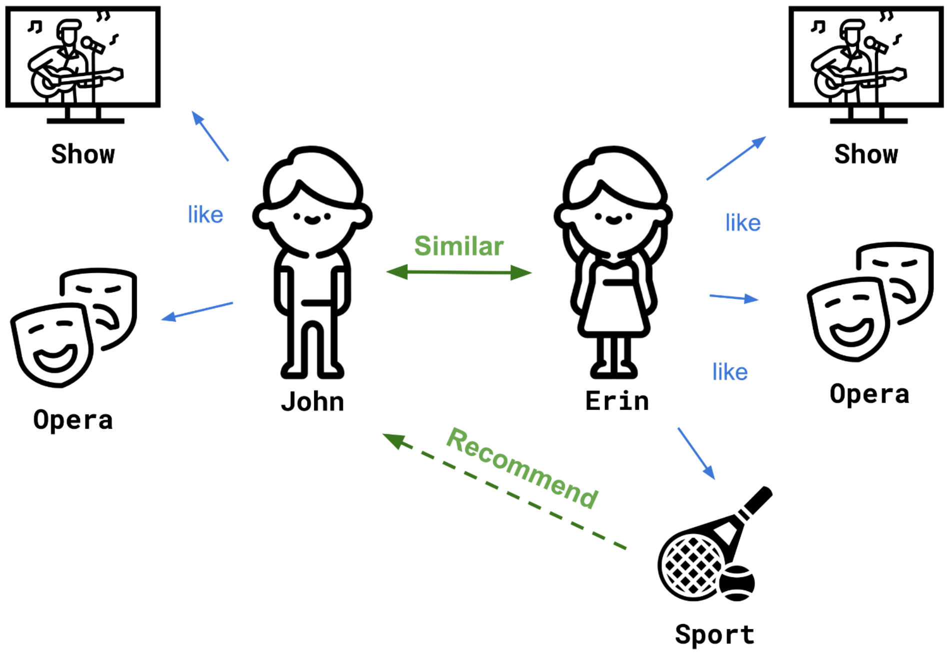


Figure 29. Mechanism of recommendation engines

The calculation of correlation coefficient which is the core of the recommendation engines can be implemented to identify the similarity between work packages. Specifically, because the work packages are composed of multiple pairs of data and BIM elements, correlation between work packages can be calculated by these paired data. Work packages with similar element-data pairs (EDPs) can be identified as similar work packages which help strengthen the linkages in the project data pool. Furthermore, the correlation coefficient between work packages are instantly updated every time a new EDP is added. This makes sure the linkages always reflect the relationship of project data and allow to continuously improve the accuracy of the correlation. For example in Figure 30, designers layout the piping design and add supporting documents such as pump specification and piping layout to finalize the EWP. On the other hand, contractors sketch the CWP with similar supporting documents. Although the designers and contractors may work in different teams and time schedules in the project lifecycle, as long as the work packages consist of similar EDPs, the similarity of these work packages are identified by calculating their correlation coefficient. Work packages with a high degree of similarity can be linked afterwards. Therefore, the linkages between these work packages are strengthened. Besides, the correlation coefficient is updated in pace with the project lifecycle. Namely, once the stakeholders add a new EDP to the work package, the linkages between the work packages are re-evaluated to reflect the relationships in the project data pool.

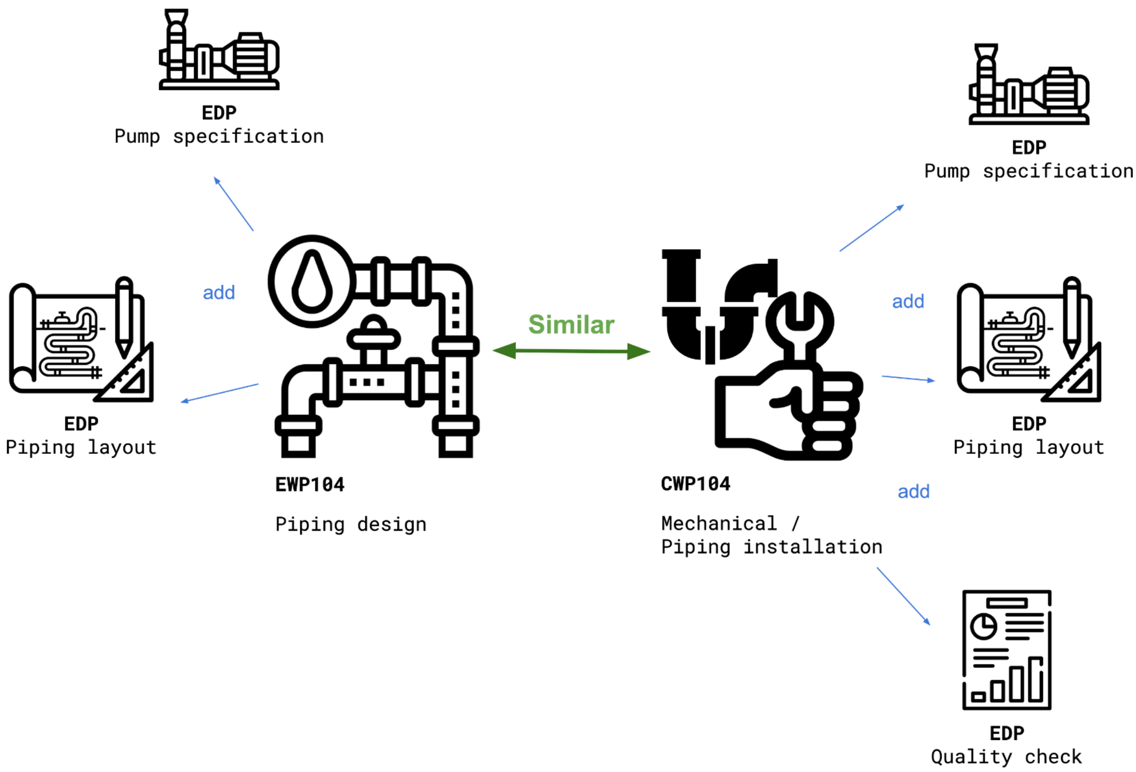


Figure 30. Correlation between work packages from the similarity of element data pairs (EDPs)

To implement the algorithm of correlation, mathematical models such as collaborative filtering which computes the relationship between EDPs and work packages can be adopted. Generally, there are implicit and explicit relationships between EDPs and work packages. Implicit relationships are the relationships not directly identified. For example, the order of the EDPs added to the work packages normally reflects the importance of the EDP. Namely, the more relevant data is added before the other data. Another example is that the number of view times for each EDP in the work package indicates the importance of the EDPs. The important EDPs generally receive more views than the others. On the other hand, explicit relationships are defined by stakeholders who add or remove EDPs to work packages. This gives a general idea of which EDPs in the project data pool are relevant to the work package. Therefore, by utilizing the implicit and explicit relationships in the mathematical models of recommendation engines, the importance rating of each EDP to the work package can be identified and serves as the foundation of computing the correlation between work packages. Then, the correlation is used as the indicator to form the linkages between work packages.

5.2.4 Module 4: Work Package Updating

The main purpose of this module is to dynamically update the linkages when work packages are updated throughout the project lifecycle. Whenever design changes occur, multiple stakeholders may simultaneously update their tasks. During the process, project data pairs in the work package may be regrouped to reflect the changes. The work package metadata, such as start time, may be updated as well. By linking the work packages through properties instead of sending design material, each stakeholder is able to access the latest work packages without complex querying or communicating. Every change in the work packages causes the work package linking algorithm to update the linkages.

Figure 27d illustrates the detailed updating process for stakeholders in response to design changes. When any change occurs, most stakeholders are required to update their work plan to align to the latest design. As every work package is separate from the others, designers, contractors, and subcontractors could modify their work packages simultaneously to reflect their parts of the design. However, some of the works may need updates from other stakeholders such as, for instance, waiting for the floor plan layout from designers. In these cases, contractors could receive the information immediately once the designer finalizes the EWP through the linkages among their work packages. Similarly, subcontractors could modify their IWPs based on the updates of CWPs. In short, stakeholders could facilitate their work packages without affecting others. Furthermore, once the stakeholders update their work packages, the rest of stakeholders receive the updates simultaneously. This maximizes the efficiency of information sharing and usage.

5.3 Case Study

5.3.1 Background

The Cockburn Cement project site located in Dongara was chosen as a test field. The preheater tower steelwork is deteriorating due to exposure. The project aimed to return the structure to its as-constructed structural integrity. The first stage of the refurbishment was on Level 5 and 6 of the preheater tower, beginning in April 2018 with a project duration of thirty weeks. Due to the small scale of the plant and the refurbishment, it was possible to observe the entire project lifecycle. As a result, the proposed approach in each stage of the project could be evaluated. By implementing the proposed framework, the increasing amount of project information aims only to be available to all project stakeholders, but also distributed to the right person at the right time.

5.3.2 System Architecture

To test the feasibility of the proposed approach, a system prototype was developed. Figure 31 shows the overall system architecture, which includes the application programming interface (API) gateway, BIM model viewer, work packaging, and work package linking modules. Each module is independent and communicates through standardized schema or events. This ensures the scalability of the system to adapt to the needs of various projects. For instance, if the geometric model of the project is complex, the BIM model viewer module may scale up its performance without interfering with the other modules. Another example is that if additional analysis of work packages linking is required, new analytical logic could be added to the current modules without affecting other modules.

The web user interface (UI) (Figure 31a) is the main interface for system interaction. As the interface could run identically on different platforms, every stakeholder could interact with the system without local installation. Furthermore, by separating the web user interface from the back-end architecture (Figure 31b-e), the user interface could be customized for each project to meet specific workflow or data needs.

The API gateway (Figure 31b) is the gate of the back-end architecture. It provides a standardized interface for communicating between the system logic and the user interfaces. Specifically, front-end user interfaces exchange data through hypertext transfer protocol (HTTP) requests to access both models and work packages. It is worth mentioning that with a dedicated module for handling requests, project data such as models, work packages, and linkages could be protected from unexpected manipulations. Specifically, only authorized operations could pass the API gateway and then manipulate project data. Additionally, this module could also distribute the loading of each module. The computing resources of the back-end services could be scaled up when needed without shutting down the entire back-end service.

The BIM query module (Figure 31c) serves as the BIM database and provides visualization tools for the system. Geometric-specific operations such as pairing project data are fulfilled by dedicated extensions in the BIM model viewer. Element data pairs required by the data preparation module of the proposed framework are created and stored in the database. For non-geometric data, this module queries and passes element data to the other modules for further data manipulation. In summary, the BIM model viewer module serves as a foundation for other modules to interact with BIM models.

The work packaging module (Figure 31d) is the integrator of the system, packaging the geometric and project data. This module performs the primary operations including data preparation and work package planning in the framework of the BIM-enabled work packaging. In this module, work package data and related files are stored in the database. The module performs create, read, update, and delete (CRUD) operations based on the requests from the API gateway. Furthermore, once work packages are created or updated, an event is sent to the work packages linking module to initiate the logic of the linkage analysis.

Lastly, the work packages linking module (Figure 31e) analyses the work packages and generates linkages whenever the work package database changes. The analysis results are stored as work package linkages in the database. This module allows for possible identification of related work packages, which is essential for collaboration across stakeholders. I.e., when a work package is updated, the assignees of the related work packages could be notified and react to the change. In terms of the linking logic, generally, work packages could be linked by referring to the same elements, having the same constraints, by their sequential order, or by the hierarchy of work packages. This logic is called once the event of a work package change is sent. However, as the linking logic may differ from project to project, it is important to ensure that there is expandability in the module. As the module is separated, there is a possibility of expanding the linking logic without interfering with the system.

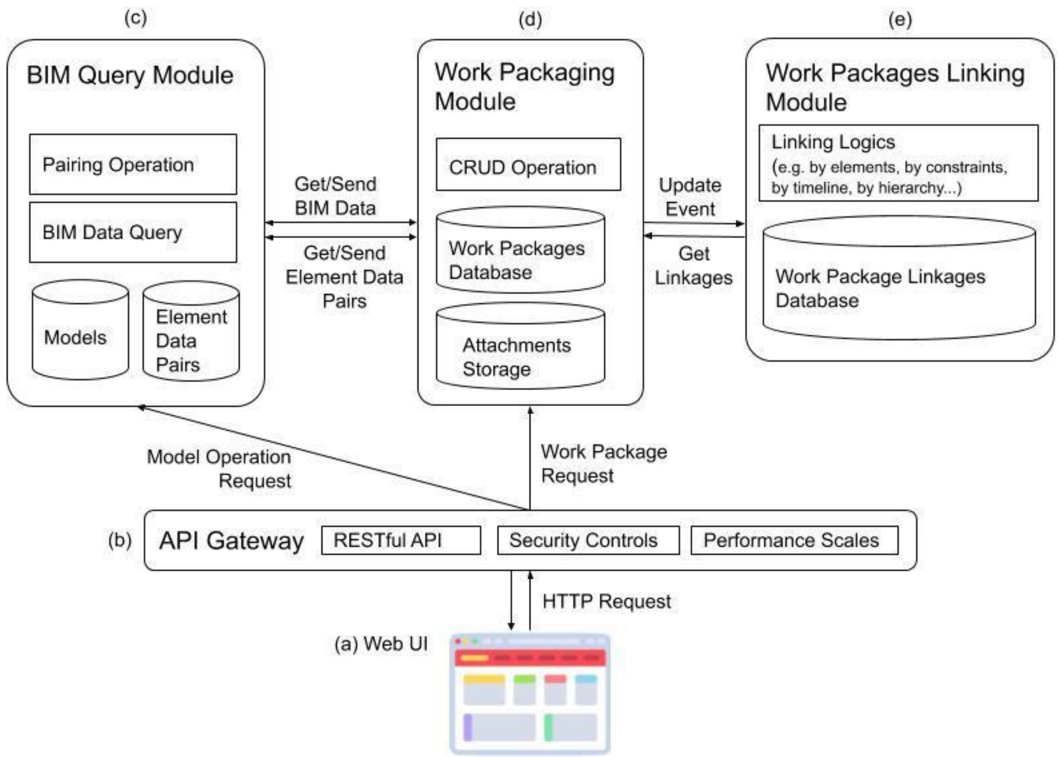


Figure 31. System architecture for the BIM-enabled work packaging

Based on the aforementioned system architecture, a system framework with data layers, a logic layer, and an interface layer was designed as shown in Figure 32. This architecture leverages the power of cloud computing and serverless concepts for flexibility in the performance and expandability of the system. First, the data layer implements cloud services to store BIM models, work packages, attachments from work packages, and work package linkages. Due to varying data formats, four database services including Autodesk Forge, Amazon Web Service (AWS) DynamoDB, AWS S3, and AWS DynamoDB Stream were selected. To elaborate on the databases, the BIM models are stored in Autodesk Forge, which is dedicated to handling the geometric and non-geometric data of the BIM models. Next, work packages are stored in AWS DynamoDB, which is a fast and flexible not only structured query language (NoSQL) database service. Work package data could be stored as rows in a series of tables without consideration of the management of the server. Next, the attachments are stored by the AWS S3 service, which is a highly scalable cloud object storage service. Lastly, the linkages are stored by leveraging the AWS DynamoDB Stream, which captures a time-ordered sequence of modification in DynamoDB tables. Once the work package tables are updated, AWS DynamoDB Stream captures the updates and the linkages are analysed correspondingly. Thus, by leveraging the serverless concept of database services, the designed databases are scalable and hosted on the cloud. All data types in the proposed system could be managed without considering the power or storage on servers, as the services could adapt immediately to computing power or storage needs from every project.

The logic layer handles the requests from the interfaces and the database operations in the system architecture. There are three major logics inside the logic layer: the model viewer logic, work packaging logic, and work package linking logic. First, the model viewer logic adopts the Autodesk Forge platform for manipulating the BIM models according to requests from the interface layer. Second, the work packaging logic implements AWS Lambda, which is a computing service that hosts code on the cloud. The CRUD operations of work packages are run on the cloud and are triggered by the interface layer. The specialty of the AWS Lambda is that it automatically scales the application while running code, which produces consistent performance. Third, the work package linking logic runs code on AWS Lambda as well. As the linking logics may vary between projects, the scalability and expandability of AWS Lambda provides a possible means of powerfully analysing work packages and adding extra linking logic.

The interface layer acts as the front door of the service. AWS API Gateway is adopted, which could create representational state transfer (RESTful) APIs. These APIs are flexible, handling multiple types of calls and delivering the corresponding services. Furthermore, it is capable of handling large amounts of traffic and authorizations from all project stakeholders. Overall, by adopting API Gateway, the interface layer provides flexible and secure control of the service at any scale.

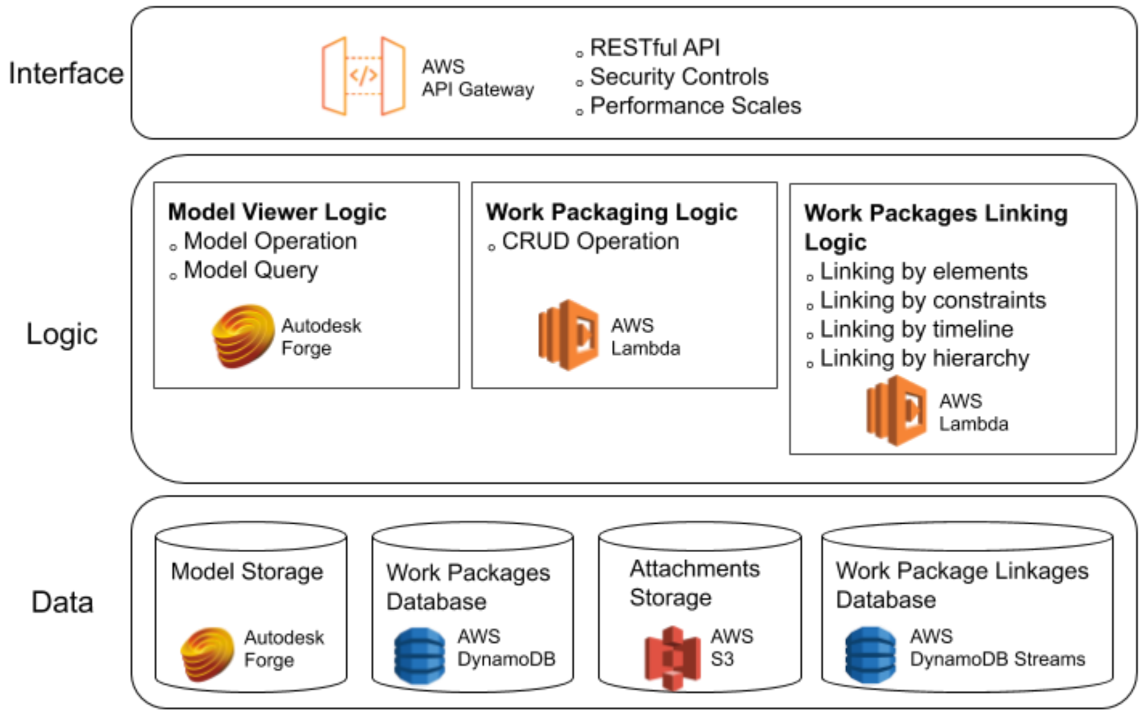


Figure 32. System framework for the BIM-enabled work packaging

5.3.3 Module 1: Data Preparation

Following the framework of the BIM-enabled work packaging, stakeholders add their data to the project data pool and pair their data with BIM elements as much as possible. As shown in Figure 33, when opening the create element data pair dialog, project data could be added on the left of the dialog. Various information formats including files, descriptions, and checkboxes could be added. On the right of the dialog, a BIM model is loaded through the viewer to query and select the related elements. In this example, the checker plate element on the top level is paired with the checklist. The process assures spatial data are added to the project information, which serves as the foundation for the work packages. In some cases, project data is not specific to certain BIM elements, such as permits, yet the data could still be added in the data preparation stage. As shown in Figure 34, a permit checklist with two check items is added without pairing with BIM elements. This shows that the schema in the database is flexible to fit the various types of project data.

In brief, in the data preparation stage, large amounts of project data are stored in the database. The project data may be stored in slightly different schemas due to the specifics of the data format. Nevertheless, by leveraging the NoSQL database, project data is organized in a single location and could serve as the foundation for BIM-enabled work packaging in the next stage.

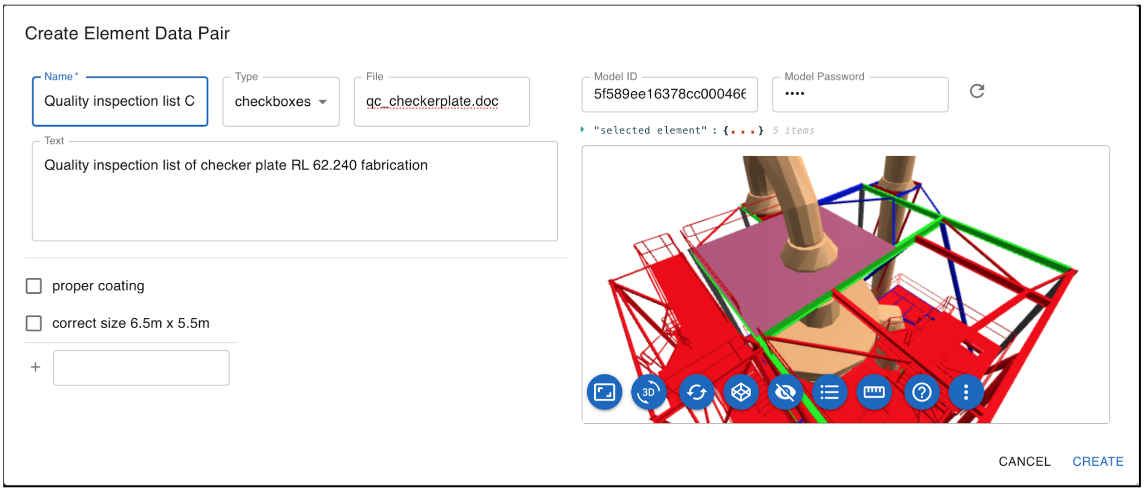


Figure 33. Pairing BIM elements to a quality inspection checklist

```
[
    {
        "updatedAt": 1595837959774,
        "checkBoxes": [
            {
                "checked": true,
                "text": "Upload plumbing permit"
            },
            {
                "checked": true,
                "text": "Upload gas piping permit"
            }
        ],
        "project": {⋯
        },
        "createdAt": 1595837959774,
        "bulletPoints": [],
        "text": "",
        "id": "de9e77e0-cfe1-11ea-b1a8-132a77b0935e",
        "name": "Permits",
        "calculableItems": [],
        "type": 1
    },
```


Figure 34. A piece of project data without BIM elements

5.3.4 Module 2: Work Package Planning and Generation

Each stakeholder outlines work packages and utilizes the paired project data to detail their work. As project data are paired to BIM elements in the data preparation stage, the corresponding BIM elements are automatically linked to the work packages when the data are added. This process eliminates potential human errors when stakeholders manually add pairs of elements and project data to work packages. Once the detailed work packages are sent to the system, the AWS DynamoDB stores the data in tables and then notifies the work package linking module for further analysis through AWS DynamoDB Stream. 91 work packages including 4 EWPs, 23 CWPs, 61 IWPs, and 3 PWPs were created, as shown in Figure 35.

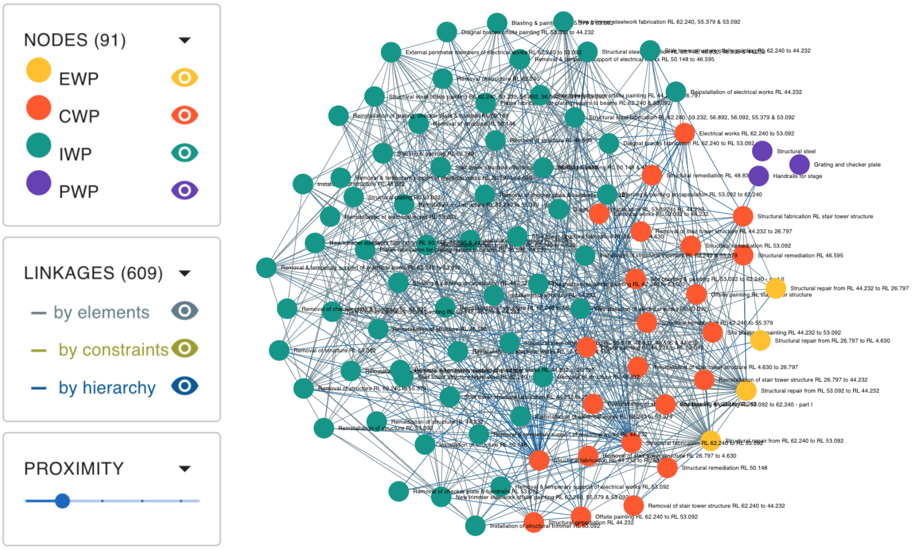


Figure 35. 91 work packages with 4 EWPs, 23 CWPs, 61 IWPs, and 3 PWPs

Figure 36 and Figure 37 present examples of work packages. Here, the contractor is outlining the piping installation work package. The general description and basic information are added as shown in Figure 36. To enrich the details of the work package, contractors could add properties that are element data pairs from the data preparation stage to the work package as shown in Figure 37. Then, the related BIM elements are automatically added to the work package by leveraging the results from the data preparation stage (Figure 36). After outlining the work packages, along with the construction stage, stakeholders could update at any time the status of the work packages to reflect the progress on site. For instance, when contractors check the list for the workspace (Figure 37), the percentage of the “workspace” group updates instantly. This provides contractors an improved understanding of the progress on each part of the tasks in a work package without continuously searching for related information.

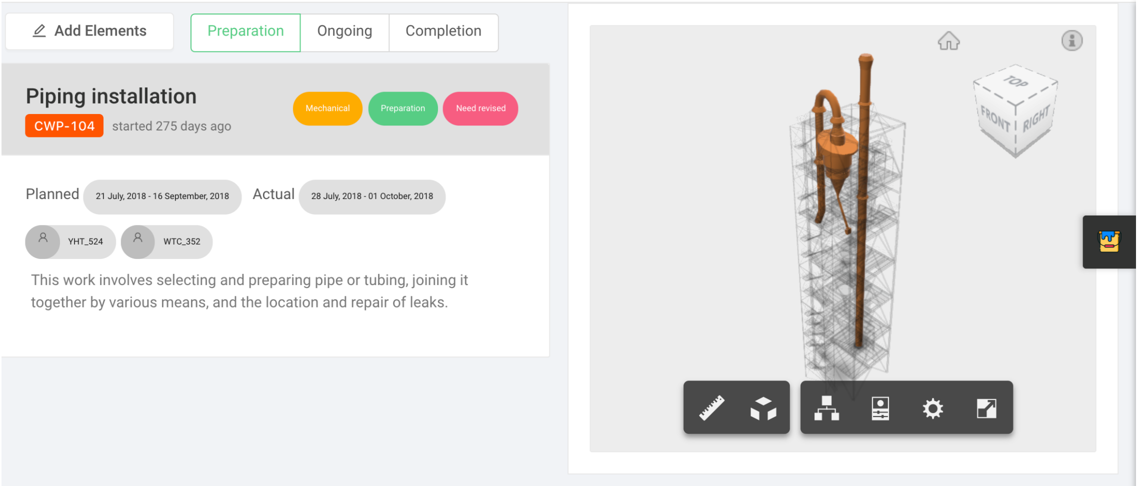


Figure 36. General description and related BIM elements for the piping installation work package

In short, with work by all stakeholders, project data could be organized through the process of detailing and updating work packages. Work packages are stored in the cloud database and the linkage analysis could be triggered by events when work packages are updated. The structured data not only helps monitor the site condition, but also reduces potential information errors while utilizing project data.

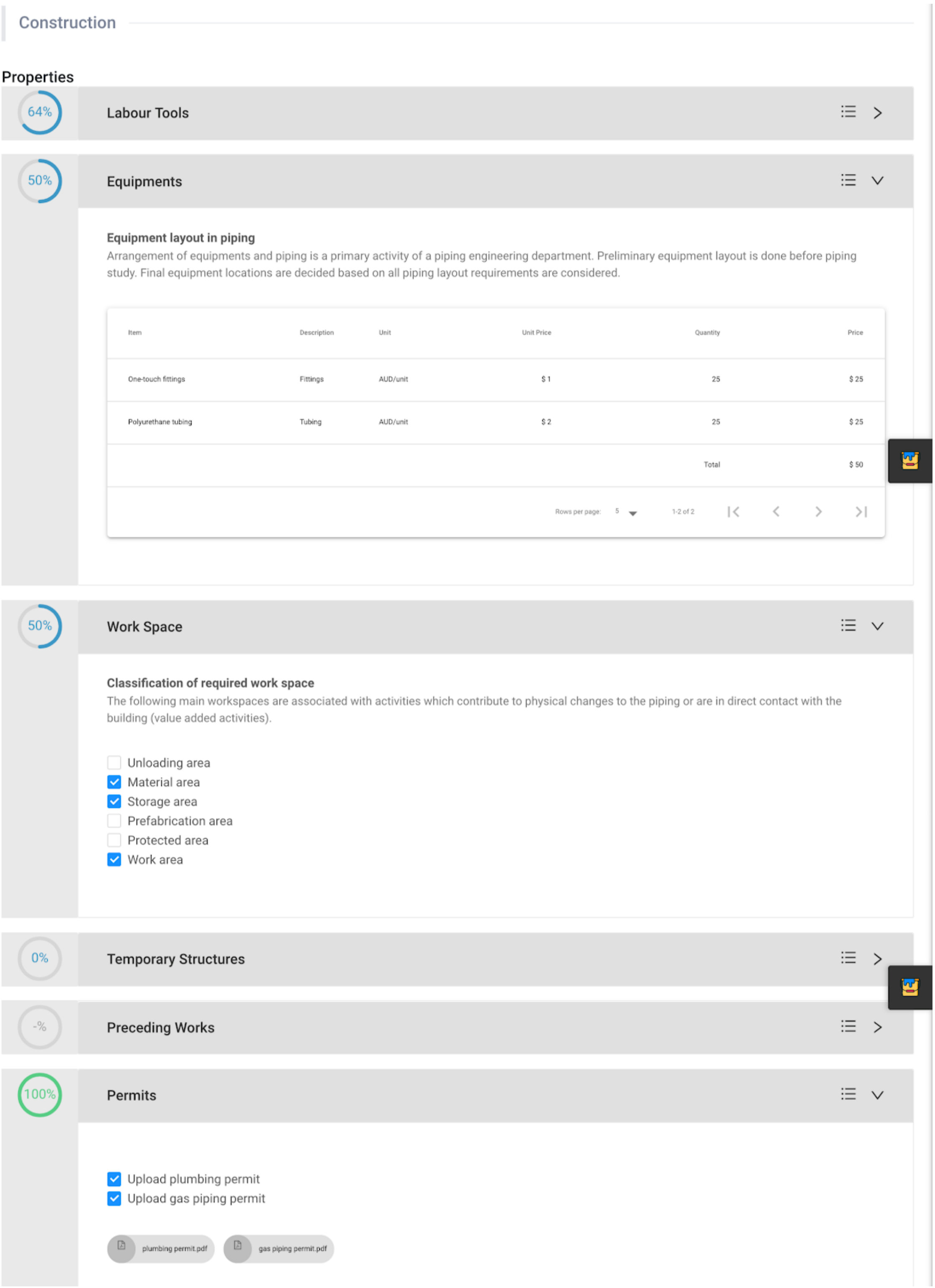


Figure 37. Project data added to the piping installation work package

5.3.5 Module 3: Work Package Linking

By collecting work packages from all stakeholders, the linkage analysis could be conducted to determine the relationships between project work packages. In the work package linking stage, after the work package update event is received, the logic in the modules analyses the updated work package and stores the linkages in the linkage table, which is hosted by the AWS DynamoDB service. There were 609 linkages automatically generated from the spatial relationships between the work packages in this project. The stored linkages suggest related work packages to stakeholders, which provide an efficient usage of the project data by acquiring as much project data as possible while managing work packages. For example, stakeholders could easily understand the details and progress of related work packages from another stakeholder by examining key properties such as status, checklists, or tables in the work package card as shown in Figure 38. Furthermore, if more information is required from the related work packages, stakeholders could click the link to navigate to the details of the related work package.

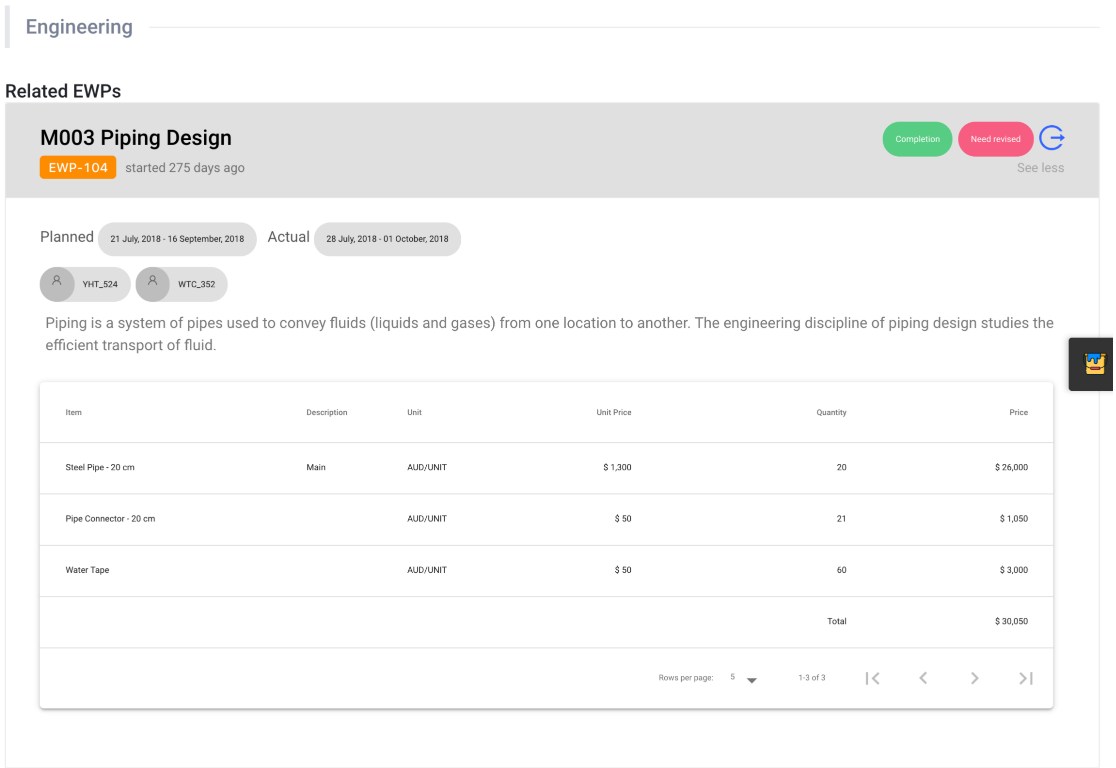


Figure 38. A related EWP presented in a piping IWP

Although the linkage logic may vary due to specific project requirements, project data paired with BIM elements are essential for the analysis as it provides a spatial dimension for reference. It can be identified that a series of work packages refers to the same targets of BIM elements. The relation between these work packages could then be further confirmed. By leveraging the AWS Lambda service, all linking logic is independent and hosted on cloud. The performance of the analysis could be scaled whenever needed. Additionally, linking logic could be added at any time without interfering with other logic. This meets the needs of work package linking as the logics could be customized project by project.

Four basic linking logics were adopted: linking by the same BIM elements, by the same constraints, in chronological order, and by the hierarchy of work packages. First, the work packages referring to the same BIM elements are linked. This suggests the work packages to stakeholders whose work packages have the same targets. Second, the work packages are linked if they add the same project data pairs. This is because if two work packages are added to the same project data pairs, they may have the same constraints to complete their work. This shows the impact of constraints to the work packages in the project. Third, work packages could be linked chronologically by identifying the execution time period on the project schedule. This illustrates the order of work packages and provides a global view of the schedule in the project. Lastly, packages could be linked by the hierarchy of work packages, which is recorded from each stakeholder while they manage their own work packages. This helps in understanding the structure of the work in each discipline.

Figure 39 and Figure 40 show an example of the linkages for "Structural fabrication RL 44.232 to RL 53.092", which is a CWP linked to one EWP and twenty-six IWPs. The linkages were created following the logic of the BIM elements and the hierarchy of work packages. Specifically, the linkages were created between the EWP and CWPs since the EWP in Figure 39 contains all of the BIM elements in the CWP and the EWP type is on the upper level of hierarchy as compared to the CWP. In Figure 40, following the same logic, the CWP contains all the BIM elements in each IWP and is in the higher hierarchical position. Consequently, the linkages for the CWP provide insight for exploring the related project data. Thus, the relationships between work packages could be formalized. Stakeholders could trace the project data through one work package to another to understand the entire picture without the time-consuming work of querying for project information.

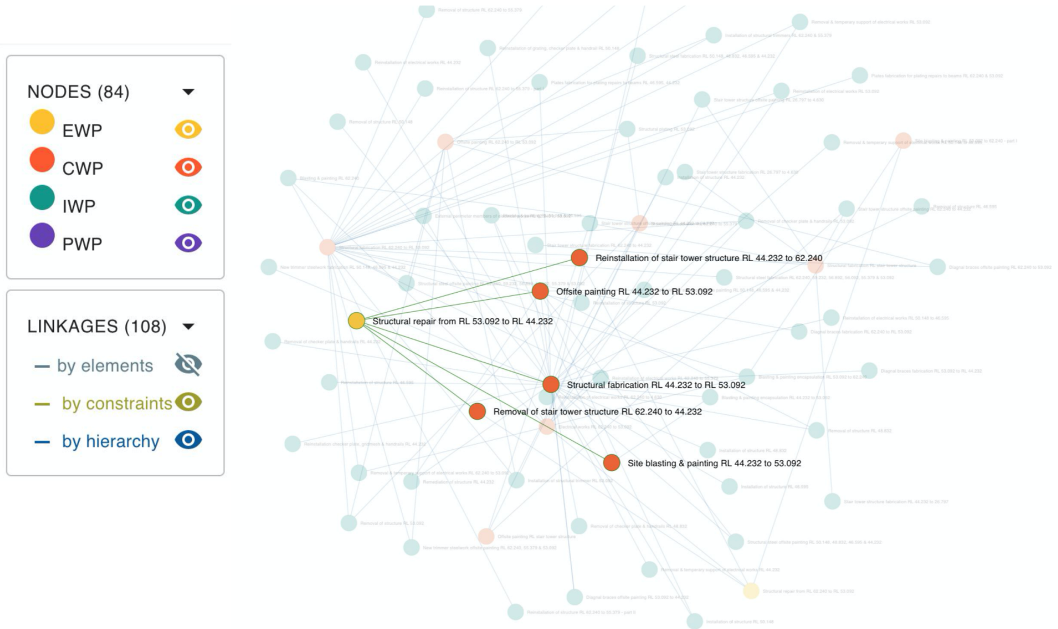


Figure 39. The EWP "Structural repair from RL 53.092 to RL 44.232" as linked to five CWPs based on the spatial data and hierarchy of work packages

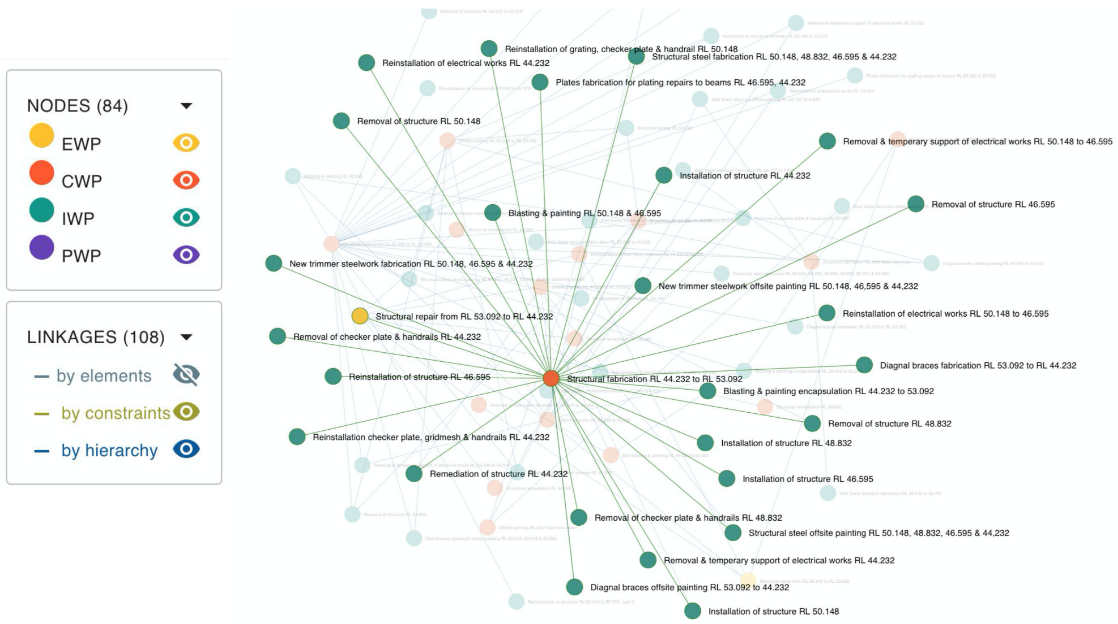


Figure 40. The CWP "Structural fabrication RL 44.232 to RL 53.092" as linked to twenty-six IWPs based on the spatial data and hierarchy of work packages

In terms of generating linkages by recommendation engines, the linking mechanism powered by collaborative filtering, which is a type of recommendation model, is designed. The linking mechanism calculates the behaviors between stakeholders and EDPs in each work package to identify the similarity. Specifically, the sequences of EDPs added to the work packages are regarded as the importance rating in the work package. The ratings then serve as the inputs for the calculation of correlation coefficient between work packages. However, it should be noted that the ratings may contain bias because they are from different stakeholders who have different standards of adding EDPs. For example, one stakeholder may prefer adding as many EDPs as possible to enrich the work packages; on the contrary, another stakeholder may only add critical EDPs to the work packages to highlight the key EDPs. Therefore, a procedure to eliminate the bias of rating is vital.

Figure 41 demonstrates the mechanism of work package linking through the collaborative filtering model. Specifically, the first row is the EDPs in the project data pool, and the first column shows the work packages created by stakeholders. Each row of the work package lists the sequence of added EDPs. In Figure 41, there are 5 EDPs and 3 work packages in the project data pool. Each rating point is marked below the sequence of EDPs. Furthermore, the rule of rating EDP is that the first added EDP in the work package is rated for highest points which equal to the average quantity of EDPs in all work packages. Then, the rating point for the subsequent EDP decreases one point in order until it reaches one point. Therefore, the rating rule weighs the points to neutralize the bias. For example, if the average quantity of EDPs among all work packages is three, the first EDP added to the work package is marked as three points. Then, the second added EDP is marked as two points, and all the rest of the added EDPs are marked as one point. As a result, all EDPs in the work packages are rated implicitly and the ratings are used for the calculation of similarity between work packages. Furthermore, bias from different standards of adding EDPs is neutralized because of the weighted points for each added EDP.

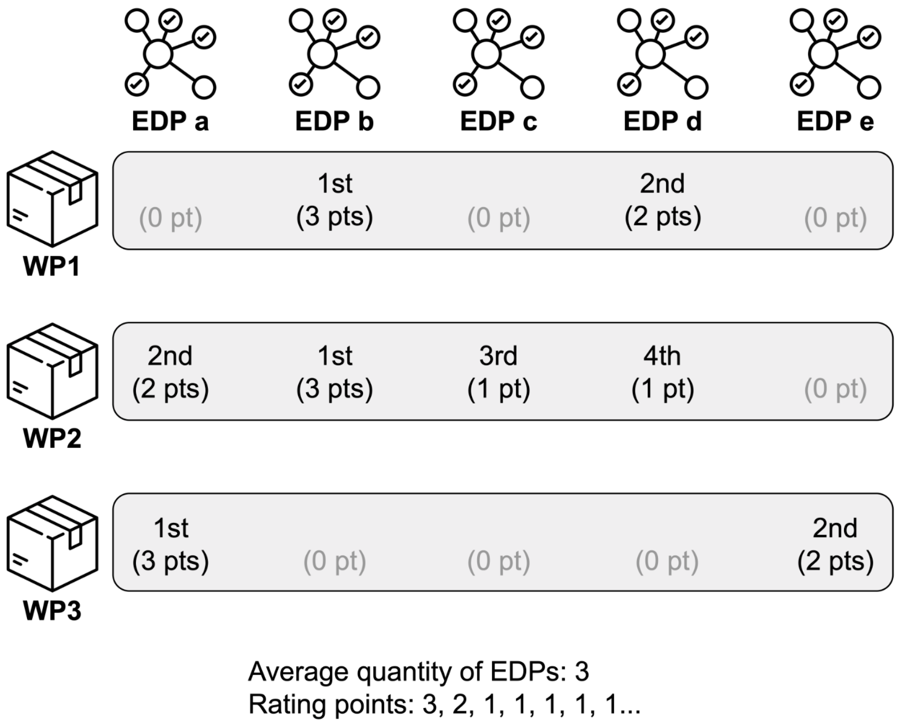


Figure 41. Mechanism of work package linking through recommendation engines

With the ratings of all work packages, similarity between two work packages can be represented as the correlation coefficient of the two work packages and calculated by the Karl Pearson's correlation (Norton, 1978):

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \, \Sigma(y_i - \bar{y})^2}} \quad \text{Equation 24}$$

r = correlation coefficient

x_i = ratings of the first work package

$\bar{x}$= mean of the ratings of the first work package

y_i = ratings of the second work package

$\bar{y}$= mean of the ratings of the second work package

The calculated correlation coefficient is a value between -1 and 1, and the higher the value is, the more similar the two work packages are.

However, the correlation coefficient may be biased when the numbers of common ratings are not large. Namely, two work packages may only have a few common EDPs, but the correlation coefficient may be very high. For example, Figure 42 calculates the correlation coefficient between work package 2 and 3 in Figure 41, and there is only one common EDP between them. In the numerator of the formula, the values from uncommon EDPs (EDP b to e) affect the correlation coefficient because the sum of the numerator is mostly decided by uncommon EDPs. Therefore, to remove the bias, only common EDPs are considered in the numerator of the formula, but all ratings of EDPs are calculated in the denominator of the formula. As a result, this weighting procedure eliminates possible bias when two work packages have little common EDPs.

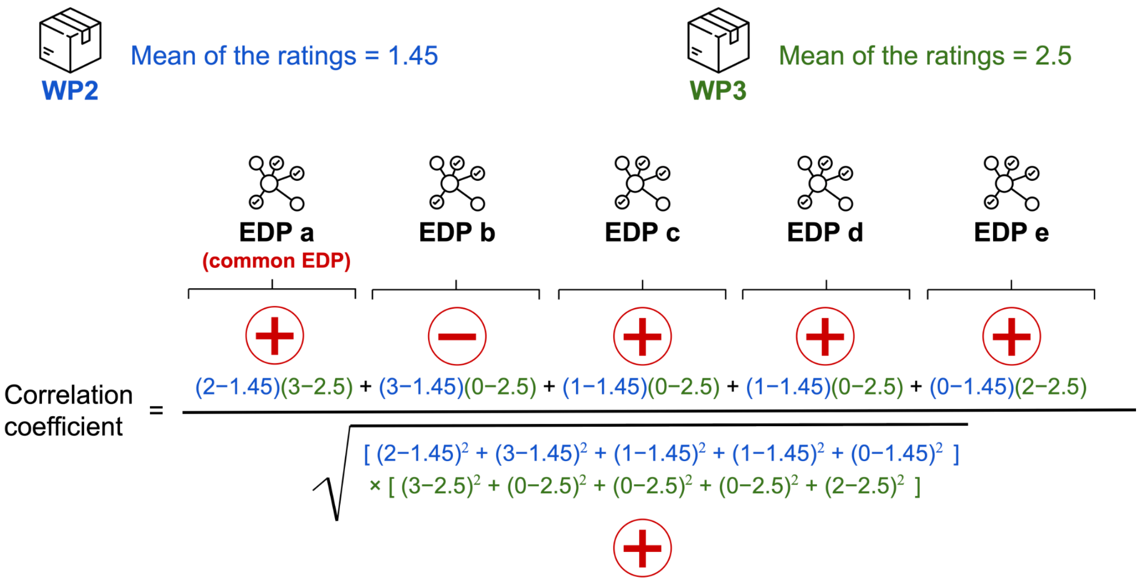


Figure 42. Example of calculating correlation coefficient with one common EDP

By implementing the collaborative filtering for work package linking, similar work packages can be identified for better information management such as understanding or sharing information. For example, the work package could find its similar work packages by the correlation coefficient between work packages. Then, stakeholders could review the work packages which have a similar scope of work but are created by other stakeholders. In Figure 43, the work package of piping design (EWP104) is created by the designer team, and the work package of piping installation (CWP104) is created by the contractor team. Although the designers work in different companies from contractors and normally work with different time schedules as well, they could simply find the piping installation work package through linkage and understand the current status in the contractor team. This helps designers track the status of the work and avoid missing useful information. Besides, EDPs in the work packages could be tracked by other teams through linkages and then be included by other work packages. This improves the information sharing by reducing the barriers of finding the related project information. In other words, the clash check report in the piping design work package (EWP104) could be found and included in the piping installation work package (CWP104) if needed. In summary, linkages among similar work packages are created for not only offering the insight of related works but also providing quick access to the relevant information which benefits the process of understanding and sharing of the project information.

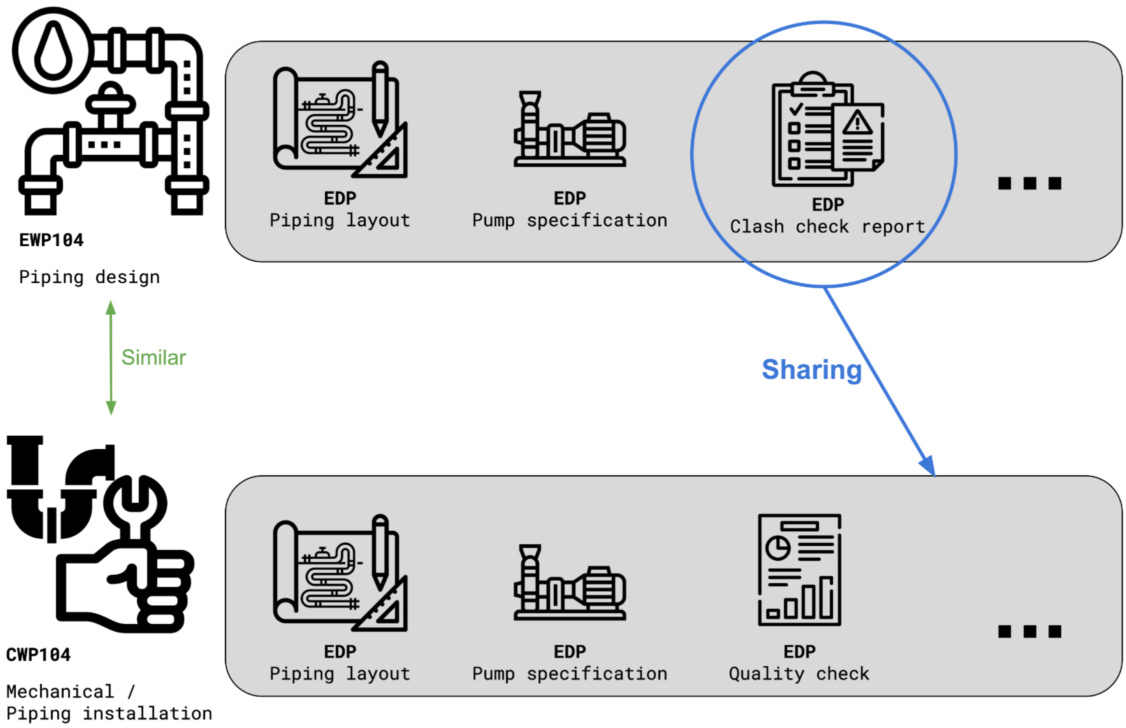


Figure 43. Mechanism of leveraging linkages for information management

5.3.6 Module 4: Work Package Updating

Design changes are inevitable in the project lifecycle, typically involving multiple stakeholders along with work package updates. During this process, stakeholders modify their parts of the design and update the corresponding work packages. Similarly, the linkages among the project should continuously reflect the changes to inform stakeholders about the changes from other stakeholders.

By leveraging the AWS DynamoDB Stream, each change in the work package database notifies the linking logic automatically. The work package linking module then analyses the linkages for the updated work package. Since the schema of work package linkages are references (Figure 44), duplication and unsynchronized work packages are avoided. Therefore, during the iteration of design changes, stakeholders could keep updated to the related and latest work packages, which aids in the collaboration among stakeholders.


```
{
    "updatedAt": 1595041776326,
    "project": {
      "id": "b5235e20-c1a5-11ea-bca8-cf9cece62aa7"
    },
    "workPackage2": {
      "id": "8440b1a0-c807-11ea-8664-4b2d761d0e63"
    },
    "createdAt": 1595041776326,
    "workPackage1": {
      "id": "52819c20-c266-11ea-b321-3f3ced2174d9"
    },
    "id": "1c4d9660-c8a4-11ea-b1cf-a7b001a58d65",
    "type": 3
}
```


Figure 44. Data schema for the work package linkage

5.4 Discussions

In this chapter, the fundamental elements of information were identified. Then, the mechanisms for linking project data were elaborated level by level. Subsequently, a framework of BIM-enabled work packaging was proposed to provide an approach for strengthening information linkages in complex projects. The system architecture was designed to validate the feasibility of the proposed approach, and a case study was presented to demonstrate the outcomes of interconnected project data.

Work packages from all stakeholders are created without dependencies on other work packages. Stakeholders are able to work together to outline their work, providing detail once more information is received from other stakeholders. Meanwhile, relationships among the work packages are generated automatically during this process. The exploration of project information through linkages is possible, which maximizes the usage of project information in decision-making.

However, there are limitations for this research. First, the process of creating element data pairs during the data preparation is tedious. Although the process may be labour intensive, time is saved when searching project data afterwards. Alternatively, customizing scripts for automatically creating element data pairs is an option for increasing process efficiency of the process. Another limitation is that due to variances in project objectives, linkage types may need to be added to build a custom layer of linkages for identifying the specific relationships among work packages.

Chapter 6: Integrating Field Sensing Information and BIM-enabled Work Packaging for Improving Information Flow in Complex Projects

6.1 Introduction

In this research, the site conditions are collected and streamed to the office in Chapter 4. Besides, linkages among the project information are built following the BIM-enabled work packaging approach in Chapter 5. To maximise the value of these well-organised project information, a common data environment specified for every possible application needs to be designed. Consequently, every application can follow the same pattern to leverage the project information comprehensively. Information flow throughout the project lifecycle can be smooth as well.

Chapter 6 proposed an integrated framework to improve the information flow in complex projects (Research Objective 3). Namely, the BIM-based field sensing approach from Chapter 4 and the BIM-enabled work packaging approach from Chapter 5 are integrated into a common data environment to accommodate the project information from multiple sources. Wasted information could be reduced by leveraging the integrated information in the data repository which leads to an improvement of information flow in the project. The proposed framework consists of three main components including fielding sensing module, data management repository module, and project management module. The details of the modules are elaborated in this chapter and two pilot studies are implemented to demonstrate the potential of the proposed framework. The results show that the proposed framework is versatile to suffice various needs of project management.

6.2 Common Data Environment for Improving Information Flow in Project Lifecycle

A framework of the Common Data Environment (CDE) for improving information flow is designed and shown in Figure 45. There are three components in the proposed framework including field sensing module, data management repository and project management module. Generally, the field sensing module is in charge of site data collection. The data management repository focuses on organising the information from multiple sources from the field sensing module or from stakeholders along with the project lifecycle. The project management module handles the diverse applications of project information such as quality management or change impact analysis. Therefore, any scenarios could leverage parts or all of the modules in the proposed framework to maximise the usage of project information which leads to an improvement of information flow by decreasing the information wastes.

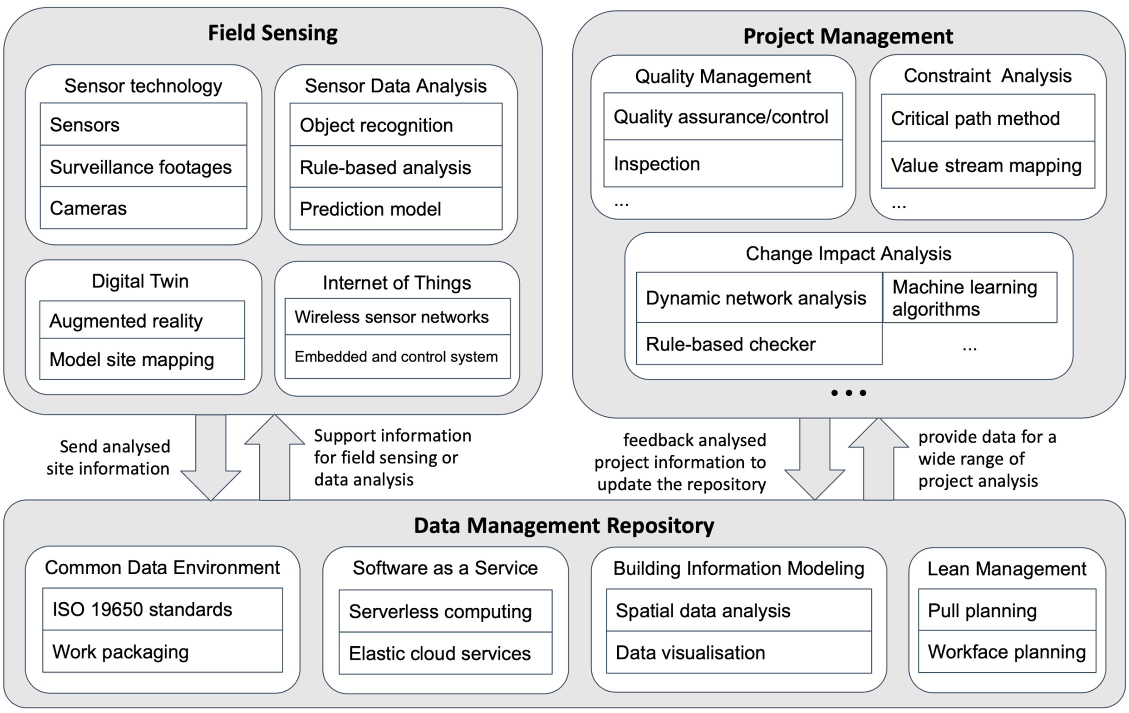


Figure 45. Common data environment for improving information flow

Field sensing module is composed of four components including sensor technology, Internet of Things (IoT), Augmented Reality (AR), and sensor data analysis. By leveraging the sensor technology and IoT, site conditions such as sensor values or surveillance footage could build a wireless sensor network and be embedded into the control system. Besides, with the capability of AR, spatial data on site could represent the physical environment and interact with the digital twin from the BIM model. Afterwards, all the sensing data aforementioned could be utilised for sensor data analysis to interpret sensing data to site information. The analysed results could be sent back to the project data repository for further usage along the project lifecycle.

Data management repository stores and organises all geometric and non-geometric information generated along with the project lifecycle. Meanwhile, it provides data for a wide range of project analysis scenarios. To support the usage, there are four main components which are the common data environment, Software as a Service (SaaS), BIM, and lean management. Each component supports different aspects of the data management in the project. Firstly, the common data environment provides a digital place to gather and share information during the project lifecycle. By following the principles in ISO 19650 series, the collaboration of project information could be layouted. Namely, the workflows of information exchanges among stakeholders are identified. Furthermore, work packaging principles help sketch the structure of project information. Stakeholders could follow a unified approach to add information to the common data environment in an orderly manner. Secondly, SaaS provides the Information Technology (IT) support for the data repository. Because of its serverless framework, the computing power is scalable with an adequate cost. The computing power is able to scale up when more and more stakeholders participate in the projects along the project lifecycle. Nothing needs to be reconfigured in the IT aspects for the data repository. This simplifies the maintenance work of the data server which is normally a difficulty for small companies. Thirdly, the BIM technology allows the project information to add spatial references. The references make the integration of project information possible which is aforementioned in Chapter 5. Besides, BIM provides a visual interface to manipulate the project information. Stakeholders intuitively explore the project information with BIM models while related project information could be shown. This makes the common data environment user-friendly which is beneficial for applying to project management scenarios. Lastly, the lean management identifies the processes of work in the project. By leveraging the pull planning and workface planning techniques, details of the project timeline are scheduled and execution on site is planned. The project information is utilised to a great extent which reduces the potential information wastes in the common data environment.

Project management module leverages the complete site data from field sensing module and the well-organised project information from data management repository to perform a wide range of applications during the project lifecycle. Although numerous scenarios could apply the proposed framework, three types of applications which are largely benefited by the proposed framework are highlighted, and these applications are quality management, constraint analysis, and change impact analysis. To start with, the quality management utilises the field sensing data as evidence to assure the criteria are met. The information from the data management repository could provide sufficient references to the criteria as well. Besides, because of the ample project information, the inspection tasks could be planned before the site trip. This procedure helps identify the critical spots by logic instead of random selections which could happen on site due to the lack of supporting information. The results of quality management could be sent back to the data management repository to maintain the integrity of project information. Next, constraints of each work and its change impacts could be analysed due to the abundant project information. Diverse algorithms of analysis could be applied to sort out the affected works by the constraints and the other works influenced by the affected works. Generally, the algorithms are based on theories, experiences, or data analysis. For example, critical path method, value stream mapping, and dynamic network analysis are the algorithms from theories. These algorithms provide logical statements to follow in the analysis. Besides, some algorithms come from experiences such as rule-based checkers. This type of algorithm could be easily modified to fit the variational situations. Lastly, some of the algorithms are supported by data such as machine learning. The analysis results could be promising because of the integrity of the project information. However, the trained model from machine learning algorithms may not be interpreted. Briefly, various applications are possible for implementations in the project management module. The wide ranges of algorithms could be selected for a dedicated analysis as well.

6.3 Pilot Study: A BIM-enabled Approach for Construction Inspection

6.3.1 Background

Quality management is one of the most important aspects in project management (Project Management Institute, 2017). In the architecture, engineering and construction (AEC) industry, construction inspection is a widely used approach for quality management in a project for decades (Burati et al., 1991).

With the growth of BIM applications (Eastman et al., 2011), more and more engineers use BIM technology on quality management during construction. The workflow for managing a BIM model for quality management has been discussed and tested in a real site (L. Chen & Luo, 2014). However, there are two challenges when using BIM in quality management. First, manipulating a BIM model in the construction site may be difficult for inspectors due to the often complicated user interface of the software. The other challenge is that all inspection tasks need to have corresponding elements already in the BIM model.

To address the aforementioned issues in current inspection practice, the idea of a BIM-enabled construction inspection approach has been proposed (Y. H. Tsai et al., 2014). First, all inspection tasks and related details are prepared before the site trip. Second, inspectors are able to finish the inspection by retrieving the prepared inspection tasks without complicated manipulation of the BIM model. Third, the inspection tasks at construction sites involve mainly data collection. Because of the mentioned features, inspections are free of possible interference from site engineers and less chances to miss the critical spots.

To implement the proposed inspection for the AEC industry, the relationships and responsibilities between different stakeholders are studied and defined. Besides, to specify the operating mechanism of the approach, the interactions among stakeholders in the approach are illustrated. All of the results are shown in diagrams which follow the BPMN standards (Dijkman et al., 2011). BPMN is a well-known process modelling language which has been adopted by many BIM researchers to describe activities and information flows of BIM-related processes (Alreshidi et al., 2015).

6.3.2 CDE-supported Construction Inspection

Following the CDE proposed in this chapter, a framework of BIM-enabled work packaging with field sensing for construction inspection is proposed, as shown in Figure 46. Similar to the CDE, there are three main modules which are field sensing, data management repository and project management. In the field sensing module, the data collection component follows the tasks defined before the site trip. Inspectors take site photos and write comments task by task. Because all of the site tasks are layouted, the works on site are straightforward and mainly involve data collection. Next, the data management repository extracts data for inspection planning and stores predefined inspection tasks from work packages. Specifically, the spatial data in the BIM model and project information in the work packages are captured to support the inspection. Inspectors are able to identify critical areas based on the extracted information and define a series of inspection tasks. The inspection tasks are stored in the data management repository and ready for the site inspection. Lastly, the project management model provides the interface for inspection planning and analysis. Both visualised interface or dedicated algorithms could be provided to assist inspectors in exploring the project. The inspectors leverage the sufficient information to analyse the critical areas and make plans. This expedites the understanding process of the conditions on site which is valuable for inspectors who are normally in charge of multiple projects at the same time.

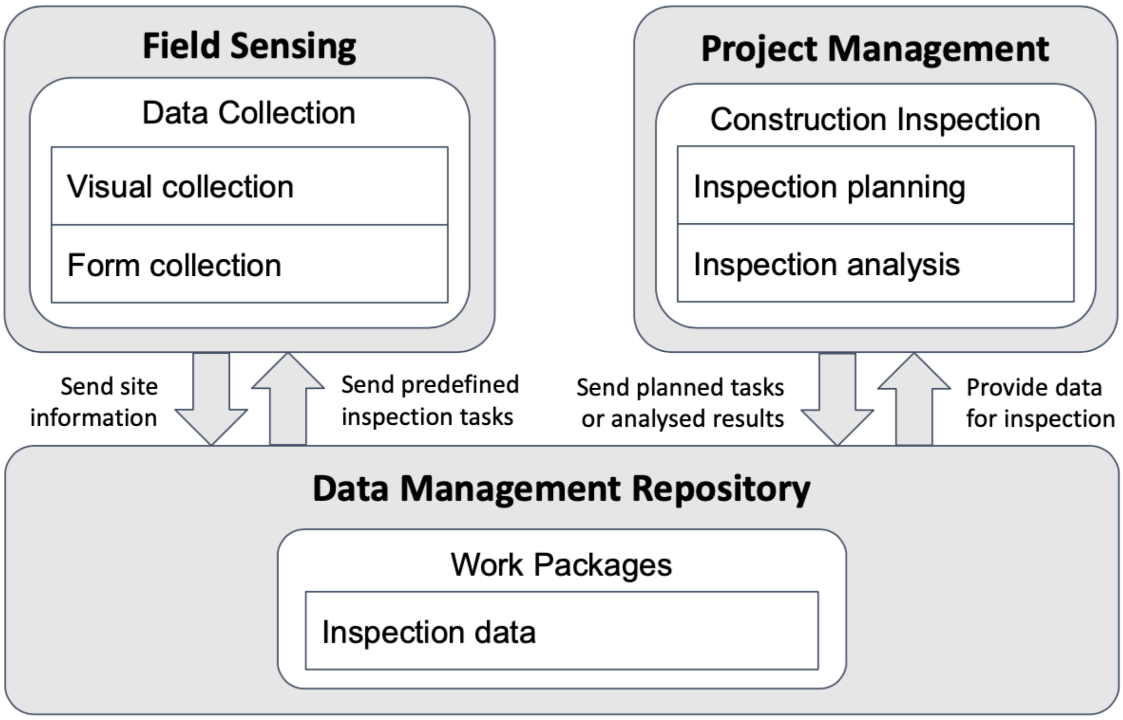


Figure 46. A BIM-enabled work packaging with field sensing framework for construction inspection

6.3.3 Implementation

There are three main stakeholders in the inspection process: designers, inspectors at office, and inspectors at construction sites. Each of them is responsible for a different part of inspection tasks in the inspection lifecycle. The activities among them are shown in Figure 47 and elaborated in the following:

1. Designer at office: At the design stage of the project, designers developed their designs in a BIM model. During the development process, designers may note critical or special spots in their designs that require careful inspection to ensure satisfaction of design intent, for example, special rebar arrangement at some joints. Designers can mark the notes in the BIM design model and pass them to the

inspectors at the construction. Inspectors are able to know the critical spots in the project and keep an eye on them within the whole construction stage.

2. Inspectors at office: Construction inspection is usually planned before the beginning of construction. Inspectors follow the required checkpoints in the plan to execute inspections at construction stage. The BIM model allows inspectors to discuss all inspection items before a site trip. All of the inspection items can be defined and passed to the site inspectors. After the site inspection is completed by the site inspection, the inspectors at the office are notified that the prepared inspection tasks and collected site data are ready to be accessed. Inspectors can then login to the management website and manage all of the issues at the office. A round of construction inspection is done.

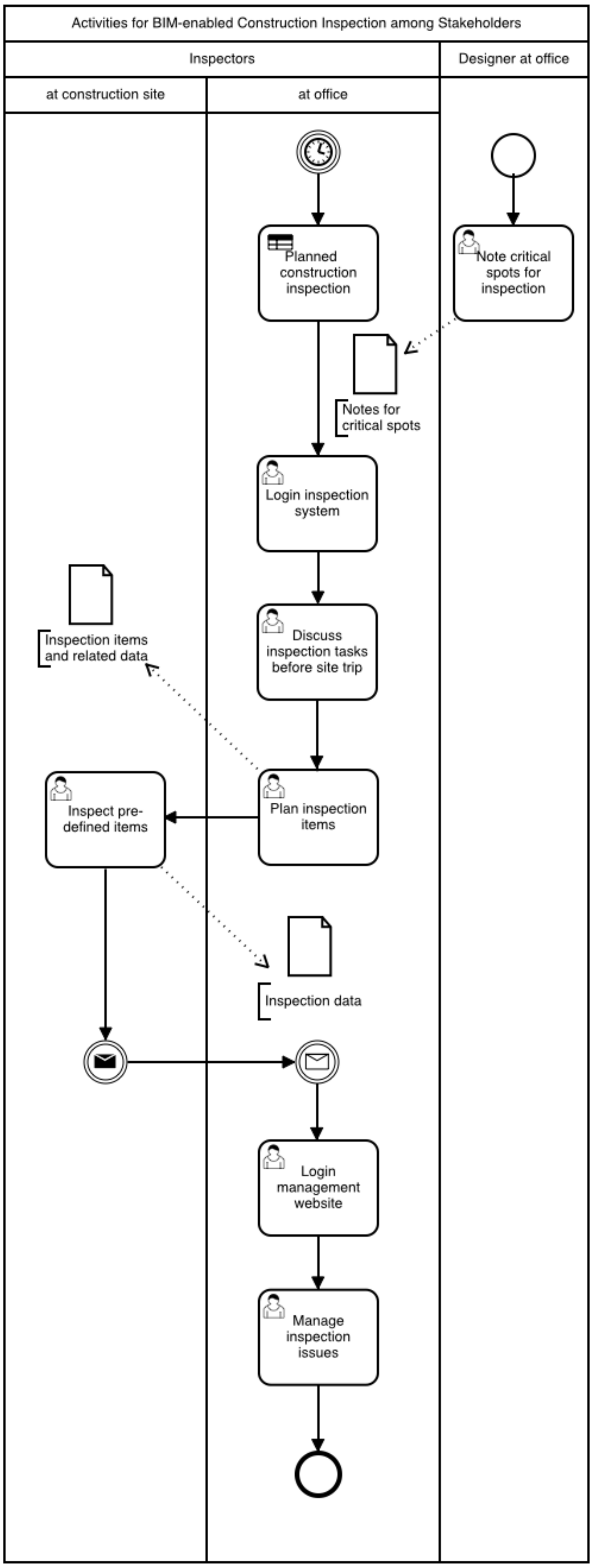


Figure 47. Activities for BIM-enabled construction inspection among stakeholders

3. Inspectors at construction sites: Once the site inspectors get the prepared tasks from the office, the rest of the tasks are straightforward and mainly involve data collection. The inspector's tasks are well defined and free of possible interference from site engineers. After the site inspection, inspectors at the office are notified and able to see the inspection data.

Based on the different activities mentioned in Figure 47, at least four components, i.e. BIM modelling tools, construction inspection database, tablet app, and management website, are needed to support the implementation. The correspondences between the components and the activities are listed as follows: BIM modelling tools and management websites serve for the inspectors at office. Tablet app is developed for site inspectors to record data at construction sites. The construction inspection database serves for integrating all of the data in different components. The functionalities and the interactions between different stakeholders and the approach are analysed in this section. Besides, the operating mechanisms of the inspection approach are illustrated in Figure 48.

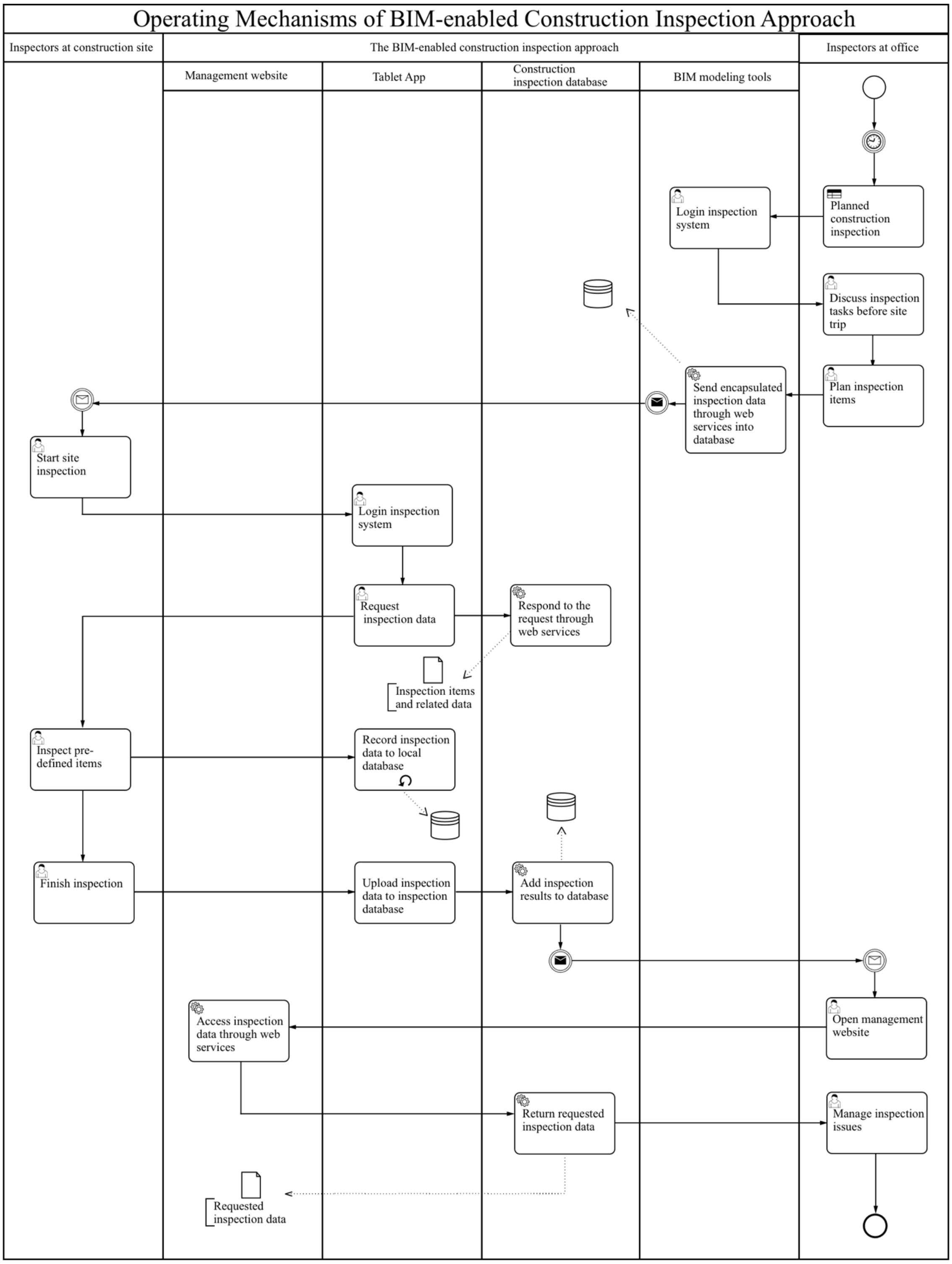


Figure 48. Operating mechanisms of BIM-enabled construction inspection approach

1. BIM tools: The BIM tools provide a digital environment for inspectors to visualize the planned inspection items and their related attributes in advance, as shown in Figure 49. Details of the construction works are already stored in the installation work packages along with the project lifecycle by stakeholders in the proposed CDE. Elements in the BIM model are marked up as well to identify the spatial relationship of the work. When preparing the inspection items, the target work packages are selected and the criteria could be added as checklists to the work packages to highlight the scope of inspection. Then, the inspection works are well prepared and rehearsed before the site trip. All of the needed information is encapsulated and uploaded to the inspection database for site inspection.

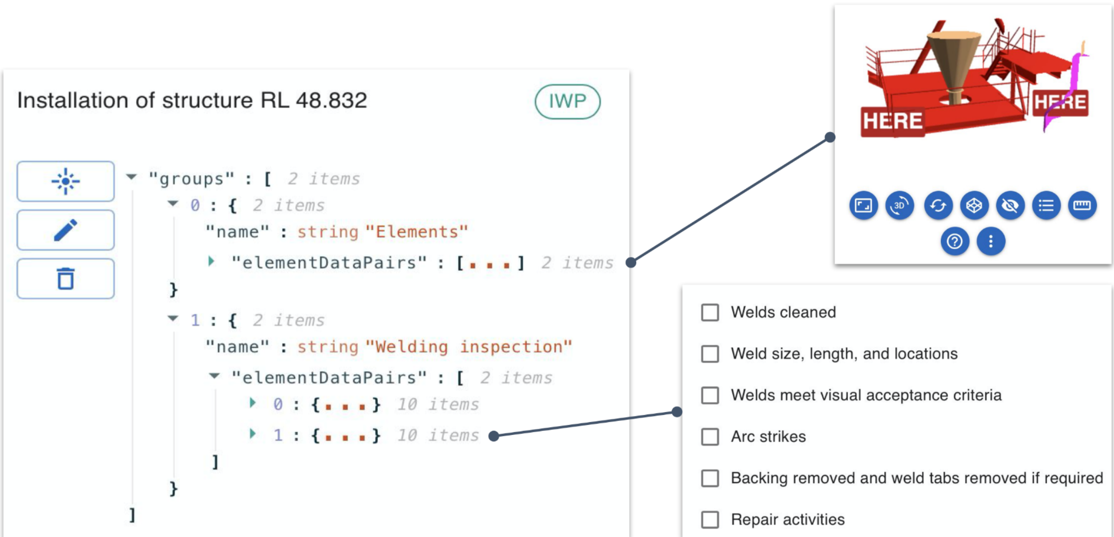


Figure 49. The inspection tasks inside an installation work package

2. Construction inspection database: The database leverages the well-organised project information in the data management repository of the CDE. Specifically, Inspection data is stored as the properties of the work packages as shown in Figure 49. Because the related BIM elements and details of the works are already

added during the construction process by site engineers, inspectors are able to utilise these data for reference with no additional cost, and the work packages are always update-to-date along the process. For example, the inspection tasks could be highlighted on the BIM model which provides a global view for understanding the scope of the inspection tasks (Figure 50). Besides, all of the data exchanges between office and site are achieved by its web services. Inspectors upload inspection data to the database at the office. After that, site inspectors access the inspection data at the construction site, perform inspection using a tablet, and upload the inspection results to the database.

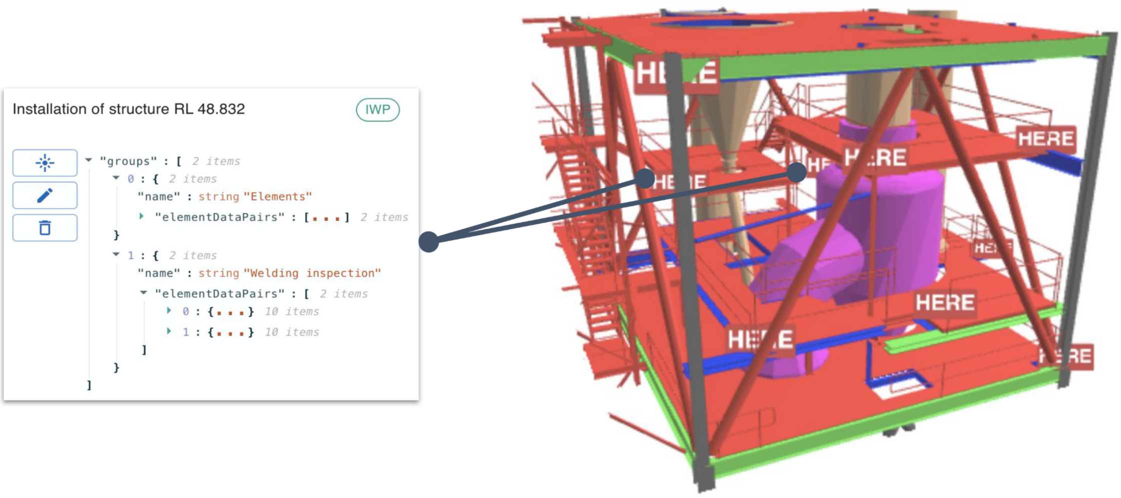


Figure 50. Scope of inspection tasks highlighted in the BIM model

3. Tablet app: Tablet app is designed for site inspection usage. Before inspectors start to conduct inspection tasks, they could download the inspection data to the tablet in advance for later use at construction sites. Because all inspection tasks are defined in advance, the inspection is straightforward and mainly involves data collection. An UI prototype is mocked up in Figure 51. There is no need to manipulate BIM models to accomplish the inspection tasks. Instead, inspectors

follow the items to complete the tasks. If additional information is needed, inspectors could tap the item for more details. By leveraging the field sensing module of the CDE, site photos and check results of criteria are recorded. After the site inspection, all the records are uploaded to the construction inspection database.

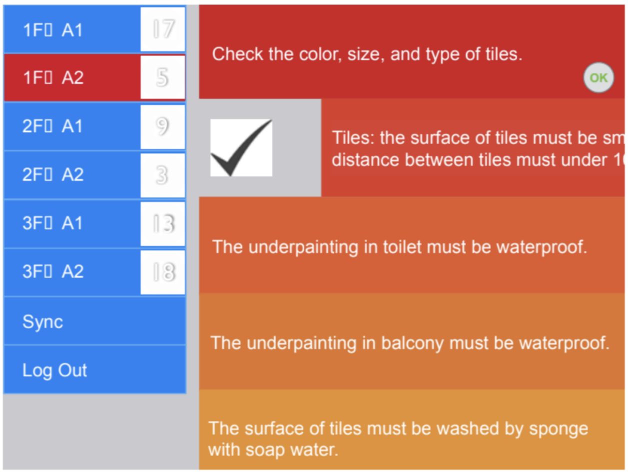


Figure 51. Prototype of the tablet UI for inspection on site

4. Management websites: Management websites are designed for managing inspection data. By leveraging the data management repository of the CDE, inspection data are integrated into the corresponding work packages. Therefore, after the site inspection, inspectors at the office can review and track the inspection data by following the status of the work packages. Then, the unsolved issues can be arranged for the next round of inspection.

6.3.4 Discussions

By implementing the proposed CDE, inspectors are able to define all of the inspection tasks before site inspection. Not only the critical spots are monitored, but the site inspection is objective and straightforward. This pilot study analyses the activities and operating mechanisms of the approach. The activity diagram defines the responsibilities among different stakeholders, while the operating mechanisms diagram describes how the activities and stakeholders interact with each other in the inspection approach. These two diagrams illustrate how the CDE-supported construction inspection approach can be implemented and shows that the CDE is capable of supporting the applications of quality management.

6.4 Pilot Study: BIM-enabled Work Packaging with Field Sensing for Constraint Management

6.4.1 Background

A constraint is a condition which impedes or delays the progress of tasks. There are numerous types of constraints such as management constraints, legal constraints, or environmental constraints. The goal of the constraint management in the project lifecycle is to identify and remove all constraints prior to the task start (Ballard et al., 2007). Because of the uniqueness of each constraint, parts or all of the modules in the proposed CDE can be applied to remove the constraints. For instance, the management constraints and legal constraints could be identified and removed through the lean management in the data management repository module. On the other hand, the environmental constraints could be solved through the combination of field sensing, data management repository, and project management modules.

A well-conducted constraint management improves the efficiency of the construction process and closes gaps in schedules. To manage constraints in practice, constraints should be identified in much detail as early as possible. In other words, once the condition changes, the derivative constraints should be timely recognised and eliminated. Therefore, controlling change and its impact is crucial in project management. In this section, an environmental constraint is selected as a pilot study to utilise all three modules in the proposed CDE. The study demonstrates the mechanism of integrating field sensing information and BIM-enabled work packaging to timely detect constraints and identify the impacts from the change.

6.4.2 CDE-supported Constraint Management

The CDE-supported approach (Figure 52) streamlines the process of constraint management by sensing the site conditions and identifying the impacts through linkages among work packages. Sensors could be implemented to continuously monitor the site conditions. In the CDE-supported constraint management, sensor values are added to the constraints which is part of the information in the work packages. Once the sensor values are abnormal, events could be triggered and several procedures such as evaluation and impacts analysis could be conducted. By leveraging the well-organised project information, work packages containing the triggered constraints are highlighted and the second degree of work packages which are the related work packages of the constrained work packages can be identified. Therefore, the constraints start to be eliminated promptly, and the second degree of work packages are adjusted to adapt the changes.

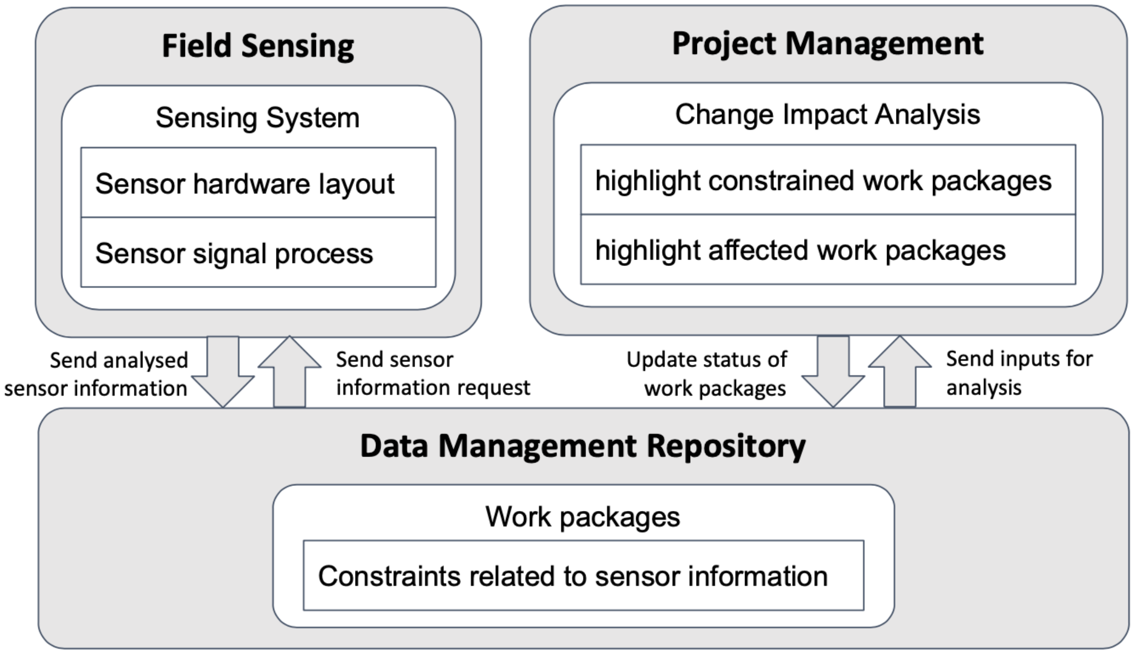


Figure 52. A BIM-enabled work packaging with field sensing framework for constraint management

The constraint management framework shown in Figure 52 follows the proposed CDE in this chapter. There are three main modules including field sensing module, data management repository, and project management module. To start with, the field sensing module utilises the smart sensing technology to monitor and collect site data. A customised hardware layout such as sensor arrays should be built to efficiently cover the area on site. Then the sensor signals should be interpreted as useful information. Next, the data management repository linked the work packages and the sensor-based constraints. Specifically, stakeholders define the constraints by the sensor values and its triggered conditions when creating or modifying the work packages. Afterwards, the work packages are able to leverage the field sensing information for constraint management. Lastly, the project management module highlights the affected work packages when constraints are triggered. Besides, the work packages related to the affected work packages are analysed to assist the impact control. In short, these three modules complete the process of constraint management. The integrated site information and work packages provide an instant and responsive interface for managers to adjust the change impacts along with the project lifecycle.

6.4.3 Implementation

An environmental constraint is exemplified to implement each module in the CDE-supported constraint management. Specifically, an on-site painting job which is normally affected by humidity and temperature is selected. By monitoring the weather on site, work packages containing the constraint could be highlighted and the second degree of work packages (affected by the constrained work packages) could be identified afterwards.

To start with, humidity and temperature are collected continuously by leveraging the BIM and field sensing technology proposed in Chapter 4.3.3. Therefore, humidity and temperature sensors are efficiently placed to cover the target area. Then, the sensor values are streamed to the office and served as the inputs for the constraint management. The CDE-supported constraint management follows the mechanism of the BIM-enabled work packaging approach proposed in Chapter 5.3.2. Constraints are defined in the data preparation stage (Chapter 5.3.3). The logics of constraints, related elements are detailed to specify the conditions. Figure 53 demonstrates the creation of weather constraint with humidity and temperature conditions. Comparison operators are specified and the related elements are selected. After the constraints are created, the constraints are added to the corresponding work packages in the work package planning and generation stage (Chapter 5.3.4). Once the work packages are updated, the linkages among work packages are re-analysed in the work package linking stage (Chapter 5.3.5). All the created constraints, work packages, and linkages are stored in the dedicated databases which are illustrated in the system architecture as shown in Figure 54.

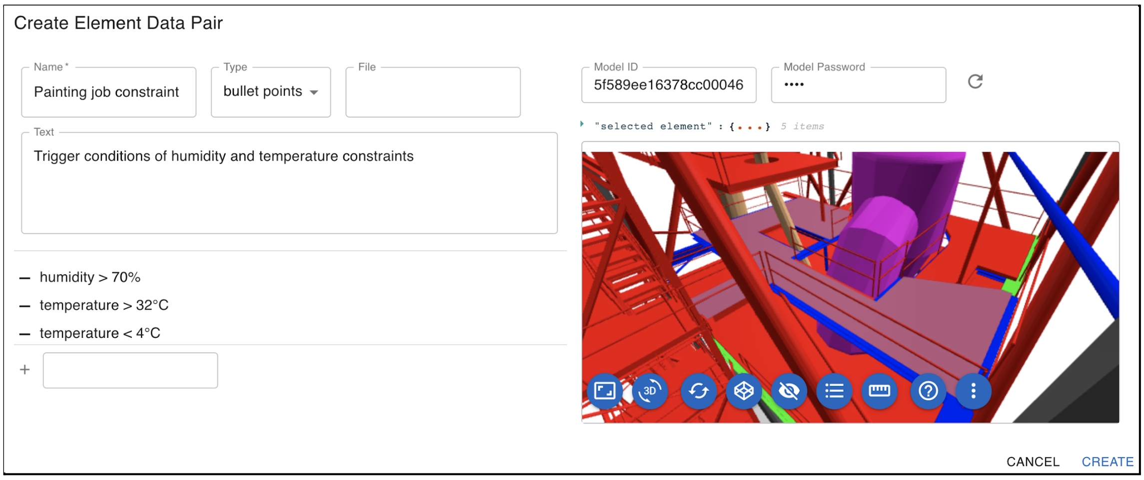


Figure 53. Create weather constraint for the work package of painting job

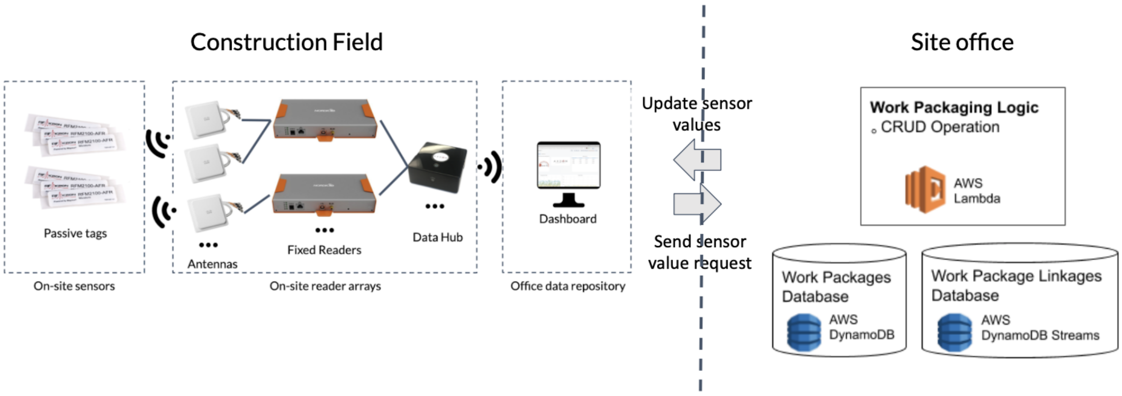


Figure 54. System architecture of CDE-supported constraint management

When the sensor conditions are triggered, the corresponding constraints and the work packages with the constraints are identified. For example, Figure 55 shows the relationship of work packages between the painting job and related works. Once the constraints of the painting jobs happen, all the related work packages can be highlighted through the linkages. The proper adjustments for those work packages could be made in the early stage.

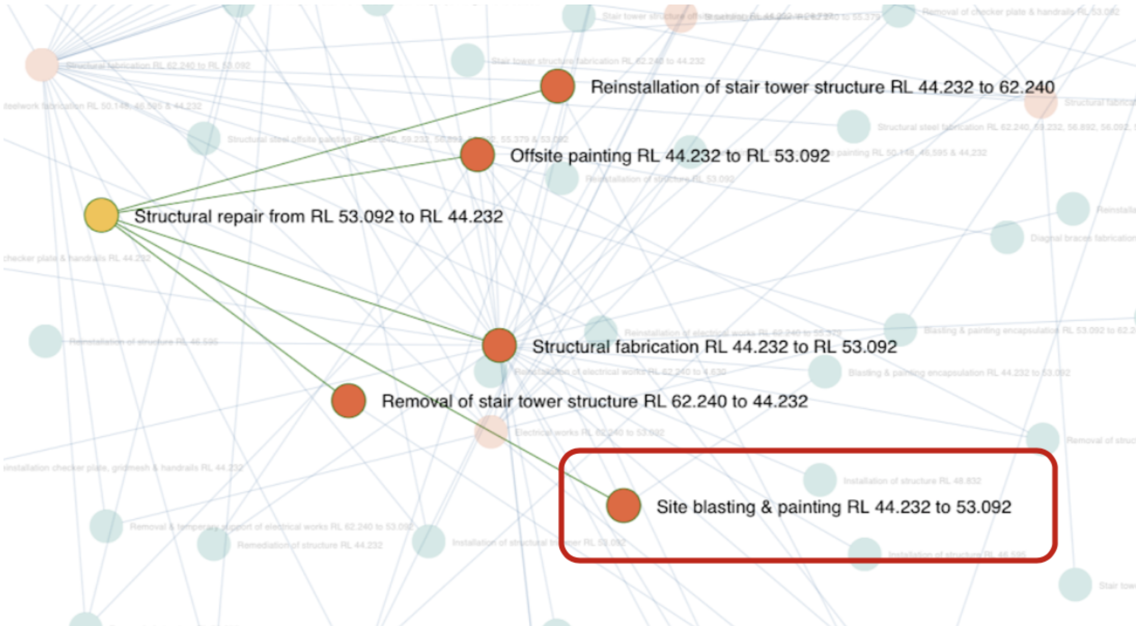


Figure 55. Related work packages to the site blasting and painting work packages

6.4.4 Discussions

The implementation of the proposed CDE for constraint management improves the work flow of the information management and reduces the possible change impacts. The field sensing module which follows the approach from Chapter 4 provides the sufficient site information for monitoring the constraints. Besides, the data management repository which follows the work packaging approach from Chapter 5 links the site information to the work packages and identifies related work packages. An example of the painting job shows the potential of the CDE-supported constraint management. This integrated approach helps improve the information flow of constraint management.

6.5 Summary

In this chapter, an integrated framework is designed to improve the information flow in the project lifecycle. Namely, a CDE framework is proposed to leverage the BIM-based field sensing approach from Chapter 4 and the BIM-enabled work packaging approach from Chapter 5. In the CDE, field sensing information and work packages are well-organised and cross-referenced in a flexible data repository. The information in the data repository could suffice various information needs of project management.

To examine the proposed CDE framework, two pilot studies including a construction inspection scenario and a constraint management scenario are exemplified. Firstly, the construction inspection scenario leverages the well-organised work packages to rehearse the inspection before the site trip. All supporting information is arranged and available for the site trip. The visual or form collection on site are integrated into the data repository as well. Secondly, the constraint management scenario utilises the field sensing information to monitor the condition on site and the data management repository to identify the constrained work packages. Specifically, because the site information and the work packages are integrated and cross-referenced, once the constraint happens, the constraints in the work packages are triggered and the related work packages are identified. In short, these two pilot studies show that the information waste is reduced. The proposed CDE is versatile and capable of improving the information flow in the project lifecycle.

Chapter 7: Conclusions, Implications, and Future Recommendations

7.1 Conclusions

This section summarises the research findings regarding the three objectives formulated in Chapter 1 to draw conclusions from the results. Theoretical contributions and practical implications are outlined to highlight the significance of the research. Besides, the recommendations are discussed to point out the opportunities for future research.

7.1.1 Research findings for Objective 1

Objective 1, titled "Monitoring site conditions with BIM and field sensing information for decision making in complex projects", targets to develop a field sensing framework leveraging BIM and smart sensing technologies to suffice the information needed in the decision making process. A sensing hardware layout was designed and the sensing capability of RFID sensors which is chosen in this research were tested. Site conditions are continuously collected and sent to the system with this design. Besides, the framework was verified in a corrosion prediction scenario, and improvements had been achieved on corrosion management when identifying potential corrosion areas during the decision making process.

7.1.2 Research findings for Objective 2

Objective 2, titled "Designing BIM-enabled work packaging for strengthening information linkages in complex projects", aims to strengthen the linkages among the project information. To start with, information flow among stakeholders along with the project lifecycle was identified. Then, a BIM-enabled work packaging framework for strengthening the information linkages was developed. To validate the proposed framework, a structural refurbishment project was tested. 91 work packages were layout and 609 linkages were automatically generated based on the proposed approach. This BIM-enabled mechanism benefits stakeholders by improved understanding of the progress of their work and related work by other stakeholders with minimal information waste.

7.1.3 Research findings for Objective 3

Objective 3, titled "Integrating field sensing information and BIM-enabled work packaging for improving information flow in complex projects", aims to accommodate multiple sources of information along the project lifecycle by designing a common data environment leveraging the outcomes from objective 1 and 2. Namely, an integrated framework for utilising project information was developed to improve information flow. A construction inspection scenario following the proposed framework was tested to verify the information integrity of the project repository. In addition, a change impact scenario following the proposed framework was exemplified to verify the sensor information and work packages could benefit the decision making process in the project lifecycle.

7.2 Summary of Theoretical Contributions

This research was motivated by the increasing challenges of project information management due to the rising amount of information from innovative designs, adoption of emerging technologies, and complicated management processes. The situation leads to an inefficient distribution of project information which accumulates wasted information and clogs up the information flow. Numerous studies have proposed approaches on linking project data to BIM objects for information management.

However, linkages among the paired information, e.g. work package linkages, have not been paid great attention to. In pace with the growth of the numbers of work packages in the project data pool, a linking mechanism should be established to enhance the quality while retrieving work packages. Namely, similar scope of work packages should be retrieved together to reduce the possibility of missing information. To achieve the work package linking, paired information in the work package should serve not only the details of the work, but also the identity among work packages for finding similar work packages. Therefore, this research puts more emphasis on the work package linking over the linking between BIM elements and project data because the work package linking is scarce yet essential to the project information management.

The first theoretical contribution, the field sensing framework from Chapter 4, acquires site conditions to the decision making process. It provides a continuous information flow to stream site conditions from site to office and interpret the sensor data in useful information to support the decision making. Besides, the collected data supports the identification of linkages among work packages. The framework demonstrates an integrated approach of collecting and analysing data which is a combination of the practical sensing applications and theoretical analysis algorithms.

Secondly, the contribution is to propose a BIM-enabled work packaging mechanism for strengthening information linkages in projects from Chapter 5. Project information from multiple stakeholders is organised, and linkages among project information are automatically generated. The mechanism provides a novel approach to arrange and analyse multiple sources of project information. The BIM-enabled work packaging addresses an essential issue which is the linkages of project information. In particular, the approach integrates project data from multiple stakeholders along with the project lifecycle. To create linkages among work packages for facilitating integration, a novel strategy with the Karl Pearson's correlation coefficient is proposed. The formula calculates correlation coefficient to identify similar work packages. It contributes to the scarce yet essential issue of information integration.

Thirdly, a theoretical data framework from Chapter 6 is proposed to implement a common data environment for streamlining information among multiple stakeholders along with project lifecycle. The versatility of the common data environment shows an insight of integrating multiple emerging technologies to suffice various demands of information. It also provides the opportunity for future research to extend advanced applications on the basis of the common data environment.

7.3 Practical Implications

This research represents an effort to streamline information flow across stakeholders. To begin with, a corrosion prediction system from Chapter 4 provides an innovative approach to management pipeline corrosions. Instead of spot check pipelines, a logical decision for pipeline maintenance could be made. Additionally, the approaches for streaming and integrating the sensor data with BIM provide a versatile data environment for applications along project lifecycle. Next, a BIM-enabled work packaging system is built, and it automatically links project information which suffices the needs for decision making by providing related project information. Particularly, pieces of project data and BIM elements are implicitly paired during the create and update process. Similar work packages are identified which helps stakeholders extract information as much as possible while decision-making without continuously querying the project data pool. Consequently, the potential information waste could be reduced. Finally, a versatile CDE which fits various demands in project management is demonstrated. Two scenarios including construction inspection and change impact of constraints are implemented to show the potential of streamlining information flow in industry.

To sum up, stakeholders along with the project lifecycle can benefit from the research. Information from the design team gives stakeholders such as contractors a better understanding of the design work while contractors manage their own work. Furthermore, when a design change occurs, the design, contractor, and subcontractor teams work together to update work packages without waiting for complete data from each other. Thus, timely information sharing and communication could be realized. Information could be shared between stakeholders at any time. There will be no or little idle time for different teams to wait for information. In short, an accurate, on time, and appropriate exchange of information could be expected.

7.4 Recommendations for Future Research

The information from multiple stakeholders along with the project lifecycle is organised and cross referenced in the form of work packages. Future research can extract the information in work packages as a basis to support the information needs of applications in the project lifecycle. It can not only reduce the work of data collection but also preserve the data integrity of project information.

Except for the applications in the project lifecycle, the well-organised information can support the information needs of facility management as well. Because the information demands from facility management are mostly added to the work packages during the construction stage, the information can be extracted from the work packages to reduce the tedious process of data collection.

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