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應用 BIM 系統化規劃施工監測影像蒐集策略

Systematic Visual Data Capture Plans for Construction Monitoring using BIM

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應用 BIM 系統化規劃施工監測影像蒐集策略

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本論文係黎芳玲（R10521732）在國立臺灣大學工學院土木工程學系營建管理組完成之碩士學位論文，於民國112年07月04日承下列考試委員審查通過及口試及格，特此證明。

Le Phuong Linh (R10521732) completed this master thesis at National Taiwan University, College of Engineering, Department of Civil Engineering, Construction Engineering and Management Division on 04-07-2023 and passed the oral examination reviewed by the following examination committee members.

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摘要

隨著人們對施工監控數位化轉型的期望增加，工地傳感器技術的使用越來越普及。沒有明確的使用策略，來自傳感器收集的視覺資料將無法得到充分利用，從而導致數據浪費。為了改善此類問題，本研究提出了一個基於視覺化方法監測建築物施工的系統框架。該框架可以提供工地數位化等級以及符合收集視覺化資料的技術給工程師參考。具體來說，從 BIM 模型中導出需要監控的構件，結合工地辨識的活動來創建基於視覺的監控計劃。該計劃提供對於監控的構件、進行中的工作、資源以及最佳的視覺化資料收集方法的建議。最後，本文通過結合實際案例研究並與多位營建業領域相關的專家進行訪談，證實了本研究框架具有可行性，有助於在工地管理和監測中應用新方法的規劃設計過程，為在施工現場實施數位化創造機會。

關鍵字：工地數位化、施工監測、BIM、施工規範

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Abstract

Sensing technology utilization in construction sites has grown exponentially due to the expectation of its impact on jobsite digital transformation for construction monitoring. However, without clear utilization strategies, the massive amount of visual data from various sensors often remains underutilized, resulting in wasted data. To address these problems, this study proposes a framework for adopting vision-based construction monitoring methods that utilize BIM and construction documents. The framework enables construction practitioners to define the digitalization level needed for their projects and then provide the appropriate techniques required through model-driven analysis. It involves extracting element information from BIM and activity information from progress taxonomy to generate a vision-based monitoring plan. The monitoring plan identifies the elements, work-in-progress, resources, and the most suitable data acquisition methods. We evaluated the method through a case study and conducted extensive interviews with experienced VDC managers. This study contributes to planning processes and creates op-

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portunities for facilitating jobsite digitalization on the construction task level monitoring.

Keywords: Jobsite Digitalization, Construction Monitoring, BIM, Construction Documents

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Denotation

BIM	Building Information Modeling
VDC	Visual Design and Construction
CQs	Competency Questions
AEC	Architectural Engineering and Construction
UAV(s)	Unmanned Aerial Vehicles
UGV(s)	Unmanned Ground Vehicles
UI	User Interface
AI	Artificial Intelligence
WIP	Work-In-Progress

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Chapter 1 Introduction

1.1 Background

The construction industry is undergoing a digital transformation. This transformation is driven due to the requirement of efficient resource management [48]. Paper-based data management processes have been applied for a long time. In order to ensure the completion of work-in-progress and supervise the activities of workers and machinery, site engineers primarily rely on a multitude of drawings. Toward applying digitalization transformation in the firms, one of the activities is integration of advanced technologies [17]. Because of the complicated management process, construction projects faces numerous challenges, such as cost overruns, rework, low project performance, poor safety records, substandard quality, and undesired productivity. The industry hopes that adopting advanced technologies and processes could improve productivity, efficiency, and sustainability. Technological innovations have the potential to address and overcome these challenges effectively. By applying cutting-edge advancements, construction firms can improve their project performance through better project planning and management [3].

When applying these high-tech approaches to projects, construction companies must consider various aspects for effective implementation. Many studies proposed BIM frameworks and workflows over the last decade. Researchers developed theoretical BIM frame-

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works to define the general requirements, processes, and policies for supporting planning, coordination, energy analysis, and maintenance [28, 40]. They also created industry-oriented information management frameworks for BIM implementation at the project level on construction sites [18, 40]. However, these methods often require manual effort to include as-built information. Recently, many researchers have developed novel computer vision methods to process visual data collected from construction sites for various applications, including progress monitoring, safety inspection, quality control, and energy analysis [37]. The results have shown that vision-based methods are critical in digital transformation. To leverage the advantages of vision-based monitoring techniques, it is essential to establish an efficient framework that enables construction firms to adopt these methods and promote digital transformation in the construction field.

Vision-based technologies offer significant potential for advancing construction processes by providing accurate, real-time data, enhancing decision-making, improving efficiency, and ensuring higher quality and safety standards. In the monitoring progress, vision-based monitoring methods have been proposed to monitor construction activities in task and operation levels [48]. For task monitoring, researchers proposed methods to recognize building elements and visualize the progress deviations based on the metaphor of traffic light colors [12]. Furthermore, a lot of element materials are classified from the images collected daily on sites using RGB-D cameras [9]. For operation monitoring, it is possible to detect entities such as workers, excavators, concrete bucket which are working on construction sites by activity recognition algorithms [29, 46]. Besides, the interaction among the entities are necessary to be analyzed, which helps understand the relationships, dependencies, and impacts of different elements within the system [47]. Due to the exploration of vision-based monitoring approaches, developing an integrated framework to

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characterize and categorize potential data acquisition methods in vision-based technologies for construction applications would facilitate a systematic investigation and documentation in this domain.

Despite the potential benefits, implementing vision-based construction monitoring technologies across building projects remains challenging. Several theoretical and practical bottlenecks hinder the digital transformation process. First, the collected visual data from various sensors is not effectively used for all monitoring analysis. Construction practitioners are not being provided with informative instructions for computer vision applications to monitor construction sites [33]. Besides, Reja et al. [37] highlighted the lack of connections between the visual sensing technologies with progress estimation. Second, many efforts have been put into applying digitalization to collect the data without thoroughly understanding the applications, which could result in more resource waste. For example, vision-based methods can only be used to monitor physical actions and objects because of their unique capabilities and limitations [38]. Therefore, Omar and Nehdi suggested that a reasonable plan was essential for properly employing these monitoring methods before significant investments [31]. To address these research gaps, the next section introduces research objectives.

1.2 Research Objectives

The research aims to develop a novel framework that facilitates digital transformation on construction sites by adopting vision-based monitoring methods. The framework defines the requirement for different jobsite digitalization levels and guides practitioners to implement it in building projects. This study develops a building element and activity

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taxonomy by to define the objects of the monitoring process. A recommended systematic visual data capture plan can be generated automatically by identifying the desired jobsite digitalization level.

To achieve that, the research objectives include:

1. Develop jobsite digitalization levels based on monitoring outcomes. This module involves creating a target range to identify the various objectives that need to be accomplished.

   Research questions: What are the outcomes of the monitoring process? What are the objectives of monitoring outcomes? What results can be attained when applying vision-based monitoring methods? What completeness level and detail level of monitoring outcomes should the project aim to obtain? Which building elements is the project aiming to monitor using vision-based techniques?

2. Develop a taxonomy of building elements and activities by utilizing construction documents to clearly define the objectives of the monitoring process. This module provides guidance on creating a document that defines the necessary activities to form a building element and activity sequence based on construction standards, UniFormat, and MasterFormat.

   Research questions: How can project managers define the activities that should be monitored? What are the processes involved in the formation of an element? What resources are necessary for a construction task? What are the names of the activities and resources for utilizing computer vision to track?

3. Develop a reference that provides guidance on how to select appropriate data acquisition methods. This study module defines the potential requirements for data

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acquisition process, including data types, technologies, and devices. The requirements correspond to the levels of digitalization at the job site, as identified in the first objective.

Research questions: Which methods should be used for visual data acquisition? Which requirements should we consider before choosing data acquisition methods?

4. Develop an automation script in Revit to export visual data capture plans from the selected jobsite digitalization levels.

   Research questions: How to have the monitoring plan from the BIM model automatically? How to summarize the element information that the project desires to capture by vision-based methods?

5. Develop a performance assessment method for project managers to assess their implementation of using vision-based monitoring methods to monitor construction sites.

   Research questions How to assess the performance of using these proposed methods?

6. Develop a guideline to implement the framework, then validate the framework by applying it to a case study and interviewing the experts who are working in that project vb to demonstrate the competency of the framework.

   Research questions: How can we instruct construction practitioners to use the framework and export reports automatically from BIM models? Is the framework applicable to the planning process? Can the proposed framework provide useful information if applied to the planning process that considers the vision-based methods adoption?

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1.3 Research Scope

To create a novel framework for vision-based monitoring methods adoption, this research clarifies different level of digitalization based on monitoring outcomes, which are task and operation monitoring in the construction domain. This study focuses on monitoring the building shell and reinforcement concrete structure part.

The interviews to evaluate the proposed framework are conducted with two visual design and construction (VDC) experts in the a case study. Experts were asked about the current task and operation monitoring process and the proposed framework's competency.

1.4 Thesis Structure

This thesis includes five chapters:

Chapter 2 presents the literature review related to vision-based methods for monitoring construction sites, information retrieval from BIM model, framework to apply vision-based monitoring methods and digitalization levels on construction sites.

Chapter 3 details the framework, including jobsite digitalization identification, element and activity taxonomy, data acquisition requirements identification, and performance assessment method.

Chapter 4 describes the implementation and evaluation of the framework.

Chapter 5 gives the research conclusions, contributions, limitations, and future works.

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Chapter 2 Related Works

This chapter comprehensively reviews key research components related to vision-based methods for monitoring construction sites. It encompasses four main sections: (1) Vision-based methods for monitoring construction sites, (2) Information retrieval from Building Information Modeling (BIM) for construction monitoring, (3) Framework for applying vision-based monitoring methods, and (4) Identification of digitalization levels on construction sites.

In the first section, the chapter addresses the current state of task and operation monitoring and explores advanced research to resolve existing monitoring process issues. The discussion emphasizes the ongoing digital transformation in the industry and the practical application of visual data collected on construction sites. Moving forward, the chapter delves into the integration of vision-based methods with BIM. It examines previous studies that utilize BIM as a foundation for implementing vision-based techniques. The subsequent section presents a framework for the practical application of vision-based monitoring methods. Next, the final section analyzes the digitalization level definition when integrating new advancements. Lastly, the chapter summarizes the identified knowledge gaps in the field. These gaps highlight areas where further research are needed to address the challenges and leverage the potential of vision-based methods in construction monitoring.

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2.1 Vision-based methods for monitoring construction sites

Effective control and management of construction sites are of utmost importance due to the multitude of activities taking place simultaneously. Construction sites are dynamic environments where various tasks, operations, and resources converge. Without proper control, these sites can become chaotic and susceptible to delays, errors, and safety hazards. Therefore, it is crucial to implement robust monitoring and control measures to ensure that activities are carried out efficiently, resources are optimally utilized, timelines are adhered to, and safety protocols are followed.

Onsite project monitoring encompasses the tracking of both task-level and operation-level information. It involves various methods, including direct observations, surveys, and interviews, to gather comprehensive data for monitoring purposes. The requirement for automation in data collection and analysis for project- and operation-level monitoring is evident due to the time-consuming nature and human error prone of traditional methods [48]. This need for automation has led to the increasing application of advanced information and communication technologies (ICT) in construction projects. Over the past decade, there has been a growing trend of utilizing ICT to address existing limitations and facilitate automatic data collection and analysis. Images and videos, easily captured and prevalent on construction sites, have emerged as widely used media [31]. Consequently, there has been significant interest from civil engineers and computer scientists in applying vision-based technology to analyze recorded images and videos for monitoring purposes automatically.

Vision-based monitoring refer to a set of innovative technologies and techniques that leverage visual sensing technologies, such as cameras, sensors, and image processing al-

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gorithms, to monitor and analyze construction projects [20]. In vision-based monitoring methods, cameras and sensors are strategically deployed across the construction site to capture visual data. This data can include images, videos, or point cloud data that represent the physical elements and activities occurring on the site. These methods harness the power of computer vision, artificial intelligence, and BIM integration to enable a more comprehensive and efficient approach to project monitoring.

To advance beyond a digitization world and autonomous monitoring, the completion of physical items contained in BIM models and the related activities can be captured through images and recognized by employing computer vision. We can automatically capture such pictures every day, thus it makes sense to use visual data to track it. The following subsections detail the previous research on automatic task and operation monitoring.

2.1.1 Task Monitoring

Monitoring task-level information involves tracking the progress of constructing building elements and ensuring the work's quality. To identify any discrepancies between the construction plans and the project's actual status, this process heavily relies on the supervision of onsite inspectors. However, it is essential to note that this method is subjective and susceptible to errors [48]. The widespread availability of affordable cameras has substantially increased the number of photographs taken on construction sites daily. Researchers have recognized the potential of utilizing these images collectively for monitoring purposes. The concept illustrated in Figure 2.1 depicts how still images can effectively be used for monitoring the progress and quality of construction projects [12, 13].

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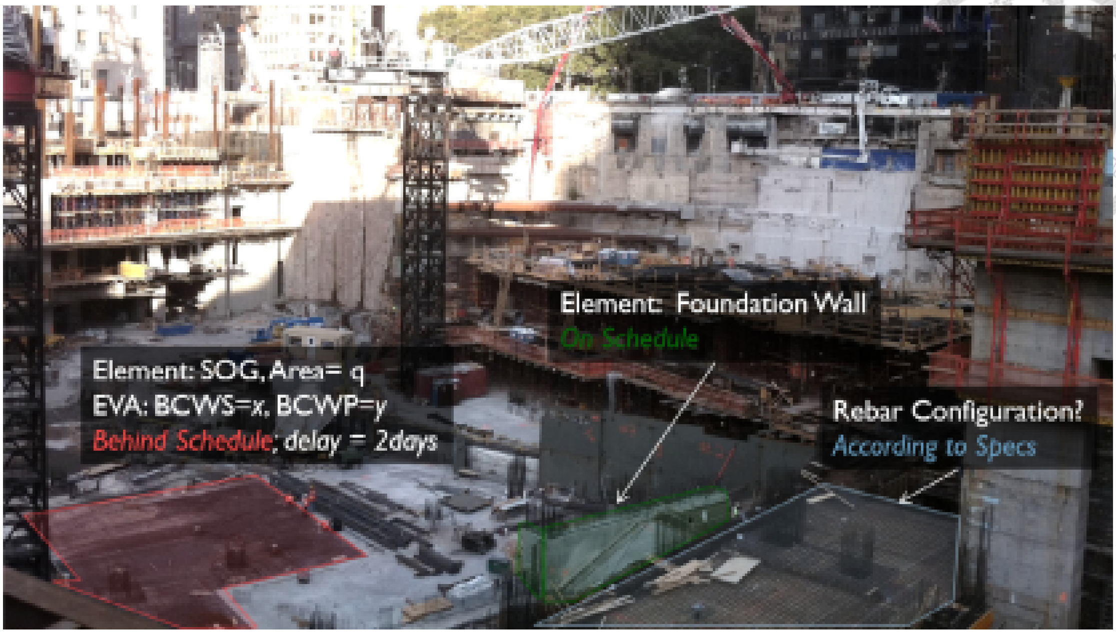

Figure 2.1: Overall concept of progress monitoring using images

Task-level monitoring refers to evaluating different components' presence and visual characteristics within a construction site. Assessment methods that rely on occupancy are utilized to determine the presence of these components. Golparvar-Fard et al. [14] have developed a methodology that uses comprehensive representations of dense image-based 3D point clouds and Building Information Modeling (BIM) data, incorporating both the as-planned and as-built perspectives. Farzad et al. [36] proposed a framework for automated simulation of construction projects. They targeted the building elements, such as walls, columns, and floors, to reconstruct those in a 3D virtual environment. Besides, another method to create an as-built model is registering the as-planned BIM model and point cloud, which is generated by photogrammetry imaging with a single off-the-shelf camera [5]. The performance deviation will be defined by comparing as-built and as-planned states through the presence of building elements. Most of the generated point clouds can express the essential structural elements by using images [26] or laser scanner [21].

Although occupancy-based assessment methods have shown progress, this approach

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fails to distinguish between the various stages of operations involved in constructing an element. In the next step, the up-to-date appearance-based methods are introduced to monitor the material of building elements [15]. These researches use images collected from RGB-D cameras to reconstruct a point cloud and apply material recognition algorithms to detect the different states of building elements such as drywall [22], concrete columns [45]. Dimitrov and Golparvar-Fard [9] introduced a Construction Material Library, which contains material categories for discriminative classification of construction materials from depth images.

2.1.2 Operation Monitoring

Operation monitoring refers to supervise construction entities and their relationships. To reduce human resources in monitoring activity operation, several researchers proposed methods to recognize activities and collect the working time of workers and machines through videos captured. Xiao et al. [47] proposed a vision-based method to automatically tracking machines via construction videos. A separate study introduced a novel approach to action recognition utilizing vision-based techniques, specifically dense trajectories, to identify workers in video footage. This was achieved by employing a Support Vector Machine (SVM) integrated with a bag-of-features pipeline. [49]. Moreover, Zhu et al. [52] designed a framework that facilitates the process of tracking workers and equipment on construction sites via videos captured by High definition video cameras. Figure 2.2 presents an overview of operation monitoring using images.

Monitoring construction activities provides valuable insights for project managers to analyze construction productivity and optimize resource allocation. Project managers can determine the number of workers actively engaged in specific activities. Tracking the

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time spent on each activity provides crucial data for analyzing construction productivity. By understanding how long it takes to complete various tasks, project managers can identify bottlenecks, areas of delay, and opportunities for process improvement. Identifying and categorizing specific activities being performed on the construction site offer insights into the sequence and progression of work. Monitoring the materials and resources utilized for each activity enables project managers to assess resource consumption and costs. Operation-level monitoring helps in tracking resource availability, identifying potential waste or inefficiencies, and optimizing material procurement and resource allocation.

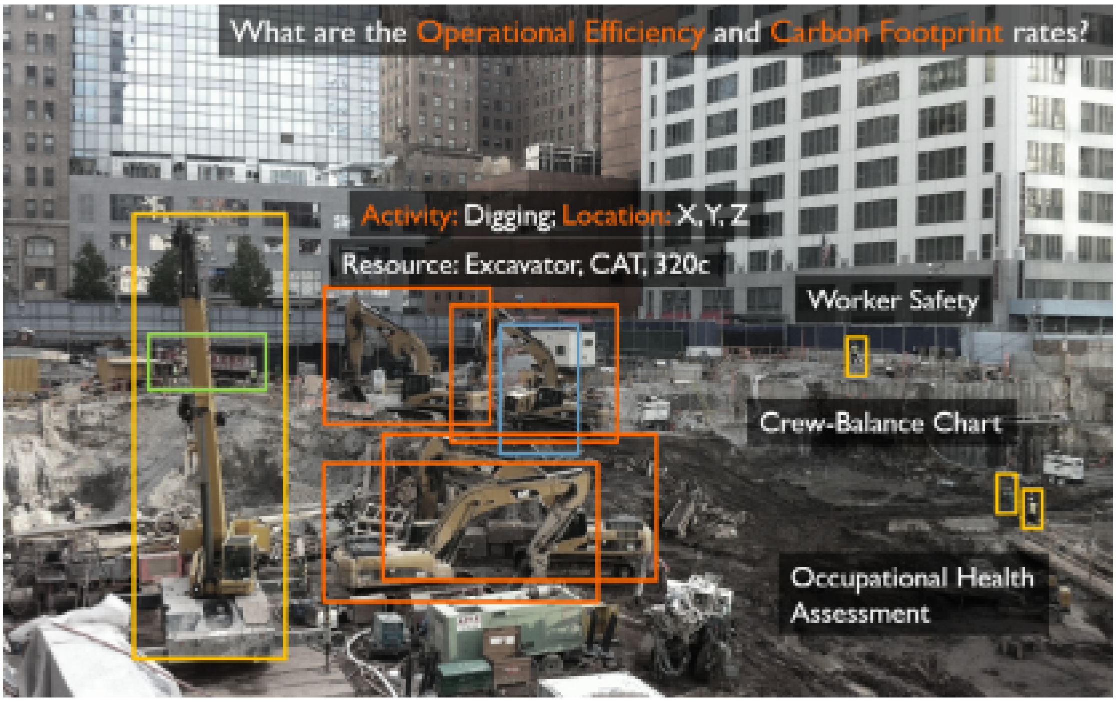

Figure 2.2: Overall concept of operation-level monitoring using images

2.1.3 Data Acquisition Methods

2.1.3.1 Data Type

In the process of creating an accurate as-built model for a construction project, the collection of various data types is crucial. These data types include text data, visual data

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and geospatial data [31]. Each type of data contributes to the comprehensive documentation and representation of the project. This chapter focuses on reviewing the data types and highlights the exceptional characteristics of visual data. Additionally, it explores the significance of text data, geospatial data, and numeric data, with a specific emphasis on environmental parameters like humidity, noise, air quality, and atmospheric pressure.

- **Text Data:** Text data encompasses information obtained from contracts, records, regulations, mandates, and standards related to the construction project [41]. These textual sources provide critical insights into project specifications, design requirements, and compliance standards. Text data serves as a foundation for understanding the project's context, constraints, and legal obligations. It enables accurate representation and documentation of the physical construction in alignment with the intended design and industry guidelines.

- **Visual Data:** Visual data is a highly valuable and remarkable type of data for creating an as-built model. It encompasses images, photographs, videos, and other visual representations captured during the construction process [25]. Visual data provides the physical characteristics, spatial relationships, and aesthetic aspects of the constructed elements. Visual data aids in detecting discrepancies, identifying deviations from the design, and ensuring the accuracy of the as-built model. It is particularly effective in showcasing the visual quality and appearance of the finished project [16].

- **Geospatial Data:** Geospatial data, including GPS or GNSS data, plays a vital role in aligning the as-built model with real-world coordinates. It provides precise location information, such as latitude, longitude, and elevation, enabling accurate georefer-

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encing of the model [31]. Geospatial data ensures that the as-built model is aligned with the physical site and facilitates integration with external geographic information systems (GIS). By incorporating geospatial data, the as-built model becomes geographically accurate and interoperable with other spatial datasets.

However, there are many outstanding characteristics of visual data include:

- **Richness of Information:** Visual data presents an abundant amount of information in a concise and easily understandable format. It conveys details that may be challenging to describe solely through text or numeric data. The visual representation allows stakeholders to grasp complex spatial relationships, material textures, finishes, and overall aesthetics.

- **Contextual Insight:** Visual data provides context and situational awareness. It captures the construction site's surroundings, existing structures, and nearby infrastructure, which contribute to a holistic understanding of the project's environment. This contextual insight enhances the accuracy of the as-built model.

- **Documentation of Progress:** Visual data allows for the chronological documentation of the construction progress. It enables a step-by-step visual representation of the construction timeline. This documentation can be useful for monitoring project milestones, conducting progress reviews, and analyzing the efficiency of construction activities.

Collecting various data types is essential for creating an accurate as-built model. Text data, visual data, geospatial data, and numeric data each contribute unique and valuable information. Visual data stands out for its richness, contextual insight, and ability to docu-

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ment progress, ensuring an accurate representation of the physical construction. However, the output of a construction project is a tangible good that can be plainly recorded and observed through visual data. There is a lot of potential for using visual data for further analysis.

2.1.3.2 Data Acquisition

To create an accurate as-built model, it is crucial to employ appropriate methods for collecting the different types of data required. This part reviews the methods commonly used to collect text data, visual data, geospatial data, and numeric data for creating an as-built model. The methods discussed include scanning and natural language processing (NLP) for text data, vision-based methods for visual data, global positioning system (GPS) and motion sensors for geospatial data, and environment sensors for numeric data [10].

- **Text Data:** Text data can be collected using scanning techniques and processed using natural language processing (NLP) methods. Scanning involves digitizing physical documents, contracts, records, regulations, mandates, and standards related to the construction project [41]. Optical Character Recognition (OCR) can be used to convert scanned documents into machine-readable text. Once digitized, NLP techniques can be applied to analyze and extract relevant information from the text data. NLP methods can include tasks such as named entity recognition, information extraction, or sentiment analysis, enabling effective data organization and retrieval.

- **Visual Data:** Photogrammetry, 3D laser scanner, Videogrammetry, and Range image are the four leading data acquisition imaging technologies. However, each technology has its unique capability and limitation to apply on construction sites

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[31]. For example, an automated approach using dense image-based to create 3D point clouds and compare them with BIMs is proposed to monitor the progress of physical elements in progress [14]. Moreover, dirt loading activity was tracked by object detection (excavator and dump truck) using Videogrammetry [39]. Otherwise, workers and equipment on construction are detected using SVM and tracked by particle filtering - Hue, Saturation, Value features [52]. However, researchers in construction focus on selecting a suitable one for their specific purposes but less on building a comprehensive approach for applying these methods on construction sites.

- **Geospatial Data:** The location and quantity information of construction people and components can be ascertained by sensors such as the Global Positioning System (GPS), Radio-frequency identification (RFID), Quick Response Code (QR code), and others to assess the progress of the construction project [44]. GPS receivers capture satellite signals to determine precise location coordinates, including latitude, longitude, and elevation [6]. Motion sensors, such as accelerometers or gyroscopes, detect movement and changes in orientation. They can be used to track the position and motion of equipment, vehicles, or workers on the construction site. These sensors provide essential geospatial data, aiding in accurate georeferencing of the as-built model and facilitating integration with GIS [11].

Despite the potential benefits, the adoption of data acquisition technology on construction sites is still in its early stages, and there is a need to guide the various technologies available and their impact on project outcomes.

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2.2 Information Retrieval from Building Information Modeling (BIM) for Construction Monitoring

It is clear that using BIM in the construction stage has many contributions to construction schedule management [24]. To establish a comprehensive construction schedule, it is crucial first to delineate the specific construction activities necessary to create building elements. These activities serve as a vital reference for site engineers. To formalize the schedule, it becomes imperative to utilize regulations, construction methods instructions, and activity codes to determine the appropriate sequencing of construction activities. Construction specifications are essential in communicating different requirements on a construction project. Those regulations provide the instruction for quality inspection and control [4], construction procedural sequence [38], construction regulation [51]. Despite the availability of construction specifications, its application is only at the design stage. At the same time, its usage can be enhanced not only in the preparation stage but also in the implementation stage. The Building Information Modeling (BIM) model offers a comprehensive list of elements, which is the foundation for generating the schedule. Although specific studies have demonstrated the potential of BIM in facilitating quantity take-off [27] its efficacy in generating schedules remains limited.

BIM-based systems also drive several benefits to construction monitoring. One of the most important benefits is that it enhances visualization by creating a digital representation of the project, allowing stakeholders to track progress and monitor various elements visually. Several researchers integrated the BIM model with the as-built model generated by visual data collected on construction sites. The availability of the Building Information Model has been increasing due to its virtual design and data management capabilities

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[42]. A BIM-based construction database system is studied to merge the different construction data by linking the BIM model with on-site documents [23]. A four-dimensional as-built model with progress information such as images and time is integrated to support the owner during subsequent life cycle stages. However, there is currently a gap in effectively utilizing element data from the BIM model in conjunction with computer vision techniques.

2.3 Framework for Applying Vision-based Monitoring Methods

Several frameworks have been proposed to facilitate the adoption of computer vision in construction monitoring. At the industry level, Moragane et al. [30] researched the factors that influence implementing vision-based monitoring methods. They presented a conceptual framework to support decision-making processes for adopting such practices. This framework considers various considerations, such as technical feasibility, cost-effectiveness, and organizational readiness, to guide the implementation of vision-based monitoring solutions on a broader industry scale.

On the project level, Reja et al. [37] introduced the CV-CPM framework, which visualizes the monitoring processes from data acquisition to progress estimation. This framework allows for the seamless integration of computer vision-based monitoring methods at different stages of the project monitoring process. By incorporating computer vision technology into each step, the framework effectively utilizes vision-based techniques and ensures that the outcomes align with the project's objectives and requirements. Qureshi et al. [35] proposed a characteristics-based framework identifying 21 effective parame-

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ters under five categories. The framework contributes to the construction industry's digital transformation process by providing a theoretical base for understanding technical parameters that affect monitoring outcomes.

Despite these advancements, there is still a need for a framework that focuses on the task level. This framework would define appropriate vision-based technologies and data processing methods for specific construction activities.

2.4 Digitalization Levels on Construction Sites

Digital transformation on construction sites includes the application of BIM, the Internet of Things, robotics, cloud and edge computing, and cyber-physical systems within the concept of Industry 4.0 [43]. Computer vision is widely researched to support the monitoring process on construction sites, which is a part of digital transformation. On the project level, previous researches assess the degree of automation in executing tasks from no electronic tools to fully-automated systems [50]. One of the limitations of previous attempts to measure digitalization in construction projects is that they assess the degree of technology used after the tasks are completed. As a result, the leading index of digitalization tends to be overlooked. Therefore, to reach the desired digitization level, it is essential to have a framework that enables a clear understanding of the potential of visual sensing technologies.

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2.5 Gap of Knowledge

Applying vision-based methods to facilitate the monitoring process in building projects is still challenging. The following is the knowledge gap summarized from the literature review.

- The lack of a framework to define appropriate vision-based technologies and data processing methods on the task level.
- The leading index of digitalization tends to be overlooked.
- The element information from Building Information Modeling (BIM) models often gets underutilized during the construction stage.
- Monitoring tasks and operations remain time-consuming and rely on humans without an implementation plan.
- The fixed surveillance installed on sites has been primarily used for security purposes, and the visual data collected on sites have been only stored, which overlooks the potential of visual data usage for progress analysis.

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Chapter 3 Systematic Visual Data Capture Plans Generation Framework

3.1 Overview

This study consists of three modules: (1) Jobsite Digitalization Level Identification; (2) Element and Activity Taxonomy Creation, and (3) Data Acquisition Mean Requirements Identification and (4) Vision-based Monitoring Plan. Figure 3.1 below illustrates the research framework for creating a vision-based monitoring plan.

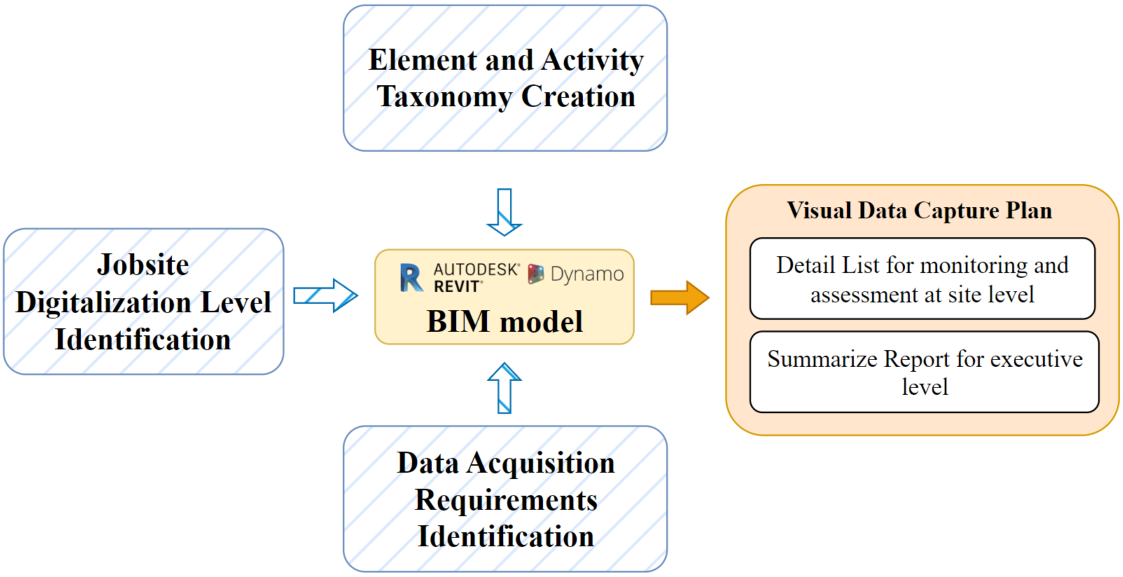

Figure 3.1: Systematic Visual Data Capture Plans Generation Framework

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In order to organize plans for capturing visual data, this study creates a range of digitalization levels, establishes a classification system for elements and activities, and identifies the requirements for acquiring visual data. The input for this process consists of three blue modules that are imported into the BIM model, while the output is represented by the orange modules that is exported automatically. Our chosen platform for working on the Building Information Model (BIM) is Autodesk Revit, and Dynamo to interact with the information within the model. The specific details of each module are explained in the following section.

3.2 Jobsite Digitalization Level Identification

The first module aims to create the jobsite digitalization levels described by the completeness and detail level of objects which are monitored by vision-based methods. Figure 3.2 below shows the steps to define different monitoring objectives of applying vision-based techniques.

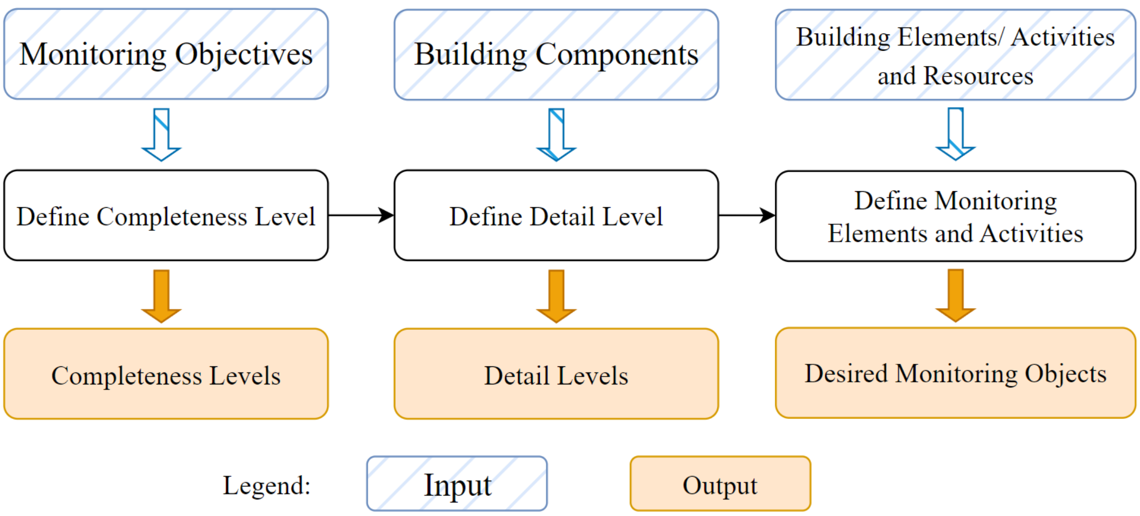

Figure 3.2: Jobsite Digitalization Level Identification Process

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3.2.1 Define Completeness Level

The first step defines the as-built output for task and operation monitoring, categorized into three levels: building element recognition, material recognition, and activity recognition. The higher levels of monitoring can provide more comprehensive information about the status of the construction site. The expected output for these levels is clarified in Table 3.1 to give a clear understanding to construction practitioners.

Table 3.1: Completeness Level

Completeness Level	**As-built Output**
Level 1 - Building Element Recognition	Geometry Point Cloud, Element Detection
Level 2 - Material Recognition	Geometry Point Cloud, Element Detection, Material Recognition
Level 3 - Activity Recognition	Entity Detection, Activity Recognition

The level one is building element recognition, where our focus is on monitoring the occupancy of different building parts. Site engineers can utilize cameras to capture images of the completed sections and analyze the progress by applying an object detection algorithm to the visual data. The result of this stage includes a geometry point cloud and the number of completed elements. For instance, if engineers want to identify columns, column images are collected by data acquisition methods and applied a detection algorithm to determine the presence of columns. The number of completed columns also is calculated to show the project's progress.

The next level of monitoring is material recognition, which entails applying more sophisticated algorithms to detect the specific type of material used in completed elements. This advanced capability allows for a detailed understanding of the construction process

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for each specific element. For instance, when monitoring the construction of reinforcement columns, multiple steps are involved, ranging from formwork installation to cement layer application. Each step utilizes distinct material layers. By capturing images with cameras and analyzing them using computer vision, it becomes possible to predict the status of the materials at a given point in time. This material recognition process provides valuable insights into the construction progress and facilitates accurate monitoring of the element's development.

At the highest level of completeness, activity recognition focuses on capturing and monitoring more complex resources such as workers and machinery. The objective is to obtain information about the number of workers engaged in the construction process, the types and quantities of machines being utilized, and the specific actions being performed by both workers and machines. To achieve this, images collected through data acquisition methods are analyzed using entity detection algorithms. These algorithms identify and classify the entities present in the images, establish relationships between them, and determine the types and quantities of entities for further analysis. This level of monitoring provides valuable insights into workforce productivity, equipment utilization, and overall progress of construction activities.

Higher levels of digitalization are attained by more information inside the BIM model and the use of visual sensing technology. Notably, even activities that do not directly involve the creation of building materials, such as earthwork and site clearance, can be effectively monitored at higher degrees of digitalization if the as-planned BIM model contains enough information about these activities. Level 4 should be monitored this type of activity. Level 5 aims to incorporate quality inspection ensuring a comprehensive assessment of the completeness of building parts. This feature improves the precision and

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reliability of the monitoring process by confirming whether pieces are fully completed or not. Furthermore, level 6 of digitization can include progress estimation capabilities. Project teams can correctly calculate installed amounts by using visual sensing technology to capture photos and advanced algorithms. This feature provides real-time visibility into project progress and enables proactive decision-making throughout the construction process. To summarize, as the information in the BIM model grows and visual sensing technologies are deployed, increased levels of digitalization enable the monitoring of diverse operations, including some that go beyond traditional building element fabrication. The addition of quality inspection and progress estimation to vision-based monitoring in construction projects improves the overall effectiveness and value of the system.

3.2.2 Define Detail Level

The second step in the process involves identifying and categorizing different building components into three levels of detail: building shell, building utility system, and interior components. This categorization helps determine which specific project components will be monitored using vision-based methods. The results of this step are summarized in Table 3.2, which provides an overview of the detail levels and examples of corresponding building components. The first level is the essential component of a building, while the upper level serves as a supplementary component that supports the building's function. It is important to note that as the detail level increases, more complicated algorithms are required to process the captured images. Additionally, higher detail levels may necessitate more flexible devices and additional time to collect visual data effectively.

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Table 3.2: Detail Level

Detail Level	**Example**
Level 1 - Building Shell	Foundation, Column, Beam, Wall, Floor
Level 2 - Building Utility System	HVAC System, MEP System, Fire Protection System
Level 3 - Interior Component	Furniture, Fixtures

At the first level of detail, the focus is on the building shell, which includes essential components such as the foundation, columns, beams, walls, and floors. These components form structural frameworks of a building and are typically prioritized in construction processes due to their importance. Monitoring processes for these components are comparatively easier as they offer clear visibility and involve fewer conflicts with other elements. Several research studies have proposed methods for detecting and monitoring these building shell components, specifically columns, walls, and floors as mentioned in the literature review. These methods leverage computer vision techniques to analyze images and identify the presence and status of these components accurately.

At the next level of detail, the monitoring focus shifts towards the building utility system, which encompasses components such as the HVAC (Heating, Ventilation, and Air Conditioning) system, MEP (Mechanical, Electrical, and Plumbing) system, fire protection system, and other utility-related elements. This level of monitoring is more challenging compared to the building shell level because these components are typically installed after the completion of the building framework. As a result, the captured images become more complex due to potential conflicts and overlaps with numerous other elements present on the construction site. The algorithms used to detect the occupancy and

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appearance of these utility system components are still under development and may not be as mature as those used for the building shell components. However, ongoing research and advancements in computer vision techniques are continually improving the capabilities in this area. Despite the challenges, monitoring the building utility system is crucial to ensure the proper installation, functionality, and integration of these systems within the building, contributing to its overall performance and safety.

At the third level of detail, the monitoring focus is on the interior components of the building, including furniture and fixtures that are installed for the customers' use and convenience. These interior components are considered less critical than the building utility system but play a significant role in enhancing the aesthetics and functionality of the building. Unlike the utility system, these components can often be installed after the completion of the building framework and utility system. The monitoring of interior components involves tracking and ensuring the proper installation and arrangement of furniture, fixtures, and other smaller items that contribute to the overall design and usability of the building. However, monitoring at this level requires more time and resources as visual data must be collected for each location, necessitating thorough documentation and analysis.

3.2.3 Define Monitoring Elements and Activities

Once the jobsite digitalization level is established, the monitoring elements and activities can be defined using the element information from BIM models and the taxonomy described in the subsequent chapter. This process aims to identify the specific components and aspects that need to be monitored by vision-based methods. The outcome of this step is the identification of the desired monitoring objects, which serve as inputs for the monitoring process. A 3D model could include structural elements, MEP (mechanical,

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electrical, plumbing) systems, equipment installations and the taxonomy, as described in the subsequent chapter, provides a classification system for defining element and activities, resources relationships.

3.3 Element and Activity Taxonomy

The second module involves creating a taxonomy showing the relationships between building elements and the required construction activities, as depicted in Figure 3.3. This taxonomy provides the monitoring objectives on construction sites. The process of creating element and activity has three main steps, which aims to give the relationship between elements and required actions to develop specific elements and the necessary resources. The activities and resources are the objects of using the computer vision process to monitor operation level on construction sites.

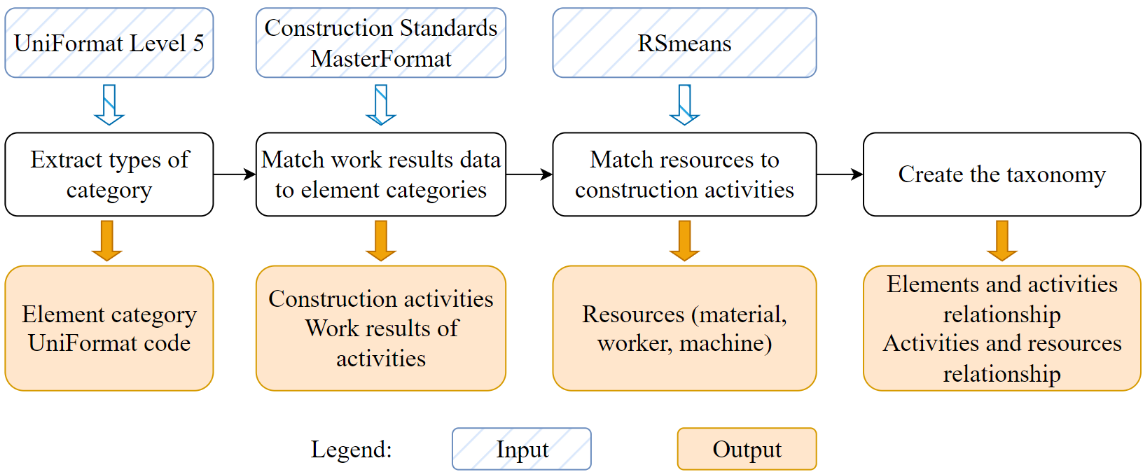

Figure 3.3: Element and Activity Taxonomy Creation

The first step is extracting the element categories from the UniFormat level 5 [7] and then matching the work results from the MasterFormat classification [8] to these cat-

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egories. UniFormat level 5 provides adequate details about the categories of elements, including their names and materials. Generally, the BIM model cannot illustrate the construction process with its elements [32]. For example, typical concrete wall construction includes reinforcement installation, formwork installation, concrete placement, curing, and plastering. However, a lack of detailed activity information in BIM models often makes monitoring activity progress challenging. Therefore, the next step identifies critical activities to construct elements based on the construction method standards and MasterFormat. For instance, we define the steps of concrete column construction based on ACI 318-19 Building Code Requirements for Structural Concrete and Commentary [1]. The work results are defined and matched to element categories. The following step involves extracting resource data for each activity from RSMeans Building Construction Cost Data [34] and complementing it with the related construction activities. This process results in an element and activity taxonomy that illustrates the relationships between elements, activities, and resources. The taxonomy can create project detail schedules and cost estimations based on model-driven analysis. The material, actions, and resources provide input information for using computer vision to analyze the visual data collected on a daily basis. Figure 3.4 shows a partial of the taxonomy including the activities, resources for the reinforcement concrete column construction.

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UniFormat Code	Element Category	Activity code (MasterFormat code)	Work Results	Material	Action	Resources
B1010240	Columns - CIP	03 11 13	Structural Cast-in-Place Concrete Forming	Wood	Install	Worker
B1010240	Columns - CIP	03 21 00	Reinforcement Bars	Reinforcement Bars	Install	Worker
B1010240	Columns - CIP	03 31 00	Structural Concrete	Concrete	Place	Worker/ Concrete Pump
B1010240	Columns - CIP	03 35 00	Concrete Finishing	Finishing layer	Formwork Removal	Worker
B1010240	Columns - CIP	07 10 00	Waterproofing	Waterproofing layer	Vertical Apply	Worker
B1010240	Columns - CIP	07 21 00	Thermal Insulation	Thermal Insulation layer	Vertical Apply	Worker
B1010240	Columns - CIP	03 24 00	Cement Plastering	Cement layer	Plaster	Worker
B1010245	Columns - Precast	03 41 00	Precast Structural Concrete	Precast Concrete	Install	Worker/Crane
B1010250	Columns - Steel	05 10 00	Structural Metal Framing	Steel	Install	Worker/Crane
B1010255	Columns - Wood	06 11 00	Wood Framing	Wood	Install	Worker/Crane

Figure 3.4: Taxonomy Table (partial)

3.4 Data Acquisition Requirements Identification

The third module defines the requirement of data acquisition application that should be considered before applying on construction sites. Figure 3.5 illustrates the process to determine the requirements for data acquisition methods to use vision-based monitoring on construction sites. The process consists of defining vision-based techniques corresponding with monitoring categories and representing data acquisition means matching the jobsite digitalization level. For different levels of completeness and detail, it is essential to define the appropriate techniques to apply to obtain the monitoring outcomes of that level.

In the first step, the vision-based techniques related to completeness levels are defined, including visual data requirements, camera specifications, technological prerequisites, and as-planned model necessities. The recommended data acquisition methods are identified as the minimum requirements for implementing vision-based approaches in

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progress monitoring through a comprehensive review of the literature. For example, the level one, recognition of a building element which is occupancy monitoring. This level's outcomes include geometry point clouds and object detection, hence the data type should be digital photos that would be captured by image cameras. After that, photogrammetry method should be utilized to create a point cloud and object detection algorithms is used to determine the presence of building components in order to achieve progress. Additionally, the level of development (LOD) needed from the BIM model and schedule are identified according to task and operation monitoring purposes. The LOD system, consisting of five levels ranging from LOD 100 to LOD 500, is utilized to specify the desired level of detail [2]. This research proposes a minimum LOD 200 for occupancy monitoring and LOD 300 for appearance task monitoring and operation monitoring. Table 3.3 presents fundamental techniques necessary to achieve the desired monitoring outcomes at each completeness level.

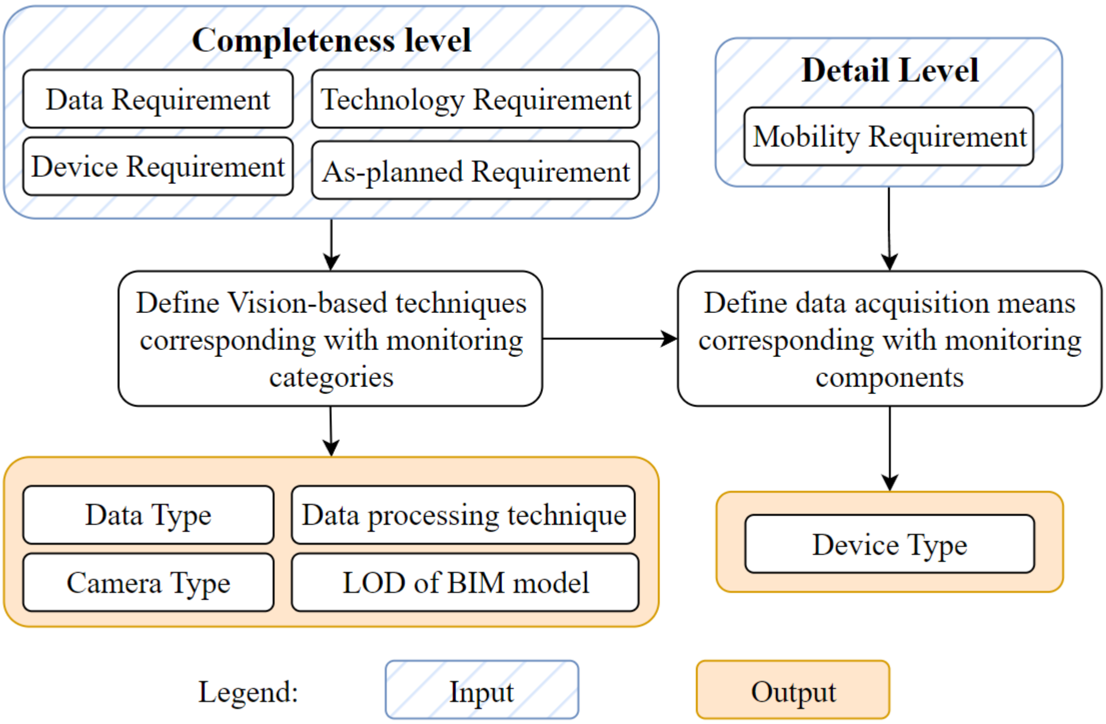

Figure 3.5: Data Acquisition Requirements Identification

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Table 3.3: Potential Data Acquisition Methods

Completeness Level	**Data type**	**Camera Type**	**Data Processing Techniques**	**As-planned Requirement**	**Reference**
Level 1 - Building Element Recognition	Digital Image	Image Camera	Photogrammetry Object Detection	BIM model LOD200	[12]
Level 2 - Material Recognition	Depth Image	Depth Camera	Photogrammetry Material Recognition	BIM model LOD300	[15]
Level 3 - Activity Recognition	Depth Video	RGB-D Camera	Pose Detection Activity Recognition	BIM model LOD300	[19]

In the subsequent step, we delve into defining the device types associated with the different levels of detail. This consideration takes into account the mobility requirements and aims to identify the most suitable devices based on the specific characteristics of camera devices. The purpose is to ensure efficient and effective data acquisition for monitoring purposes. Table 3.4 serves as a comprehensive reference, summarizing the appropriate devices for different accessibility capacities. When it comes to monitoring elements within the building shell category, a careful selection of device types is necessary. To capture a comprehensive view of the building framework, including its foundation, columns, beams, walls, and floors, a top-view perspective is crucial. In such cases, the use of UAVs, also known as Unmanned Aerial Vehicles, proves to be indispensable. UAVs offer the advan-

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tage of flexibility and accessibility, allowing for the capture of high-resolution images from different angles and heights. However, the monitoring process should not be limited to external views only. It is equally important to collect visual data from within the building, where various interior components are installed. To achieve this, alternative device types are required. Unmanned Ground Vehicles (UGVs) or portable 360-degree cameras are recommended for capturing images inside the building. UGVs provide the ability to navigate through the construction site, reaching areas that are difficult to access by other means. By deploying UGVs equipped with cameras, comprehensive visual data can be collected, enabling detailed monitoring of interior components, such as furniture, fixtures.

Table 3.4: Potential Data Acquisition Devices

Detail Level	**Device type**
Level 1 - Building Shell	UAV, Fixed Camera
Level 2 - Building Utility System	UGV, Portable 360 Camera
Level 3 - Interior Component	UGV, Portable 360 Camera

3.5 Visual Data Capture Plans Generation

After establishing the input for the planning stage, three modules are imported into the BIM models. To simplify the selection process, we utilize Dynamo, a visual programming tool, to develop a user interface. This interface allows project managers to easily choose the desired levels of detail for monitoring purposes. Once the desired levels are defined, the monitoring information is automatically exported and organized.

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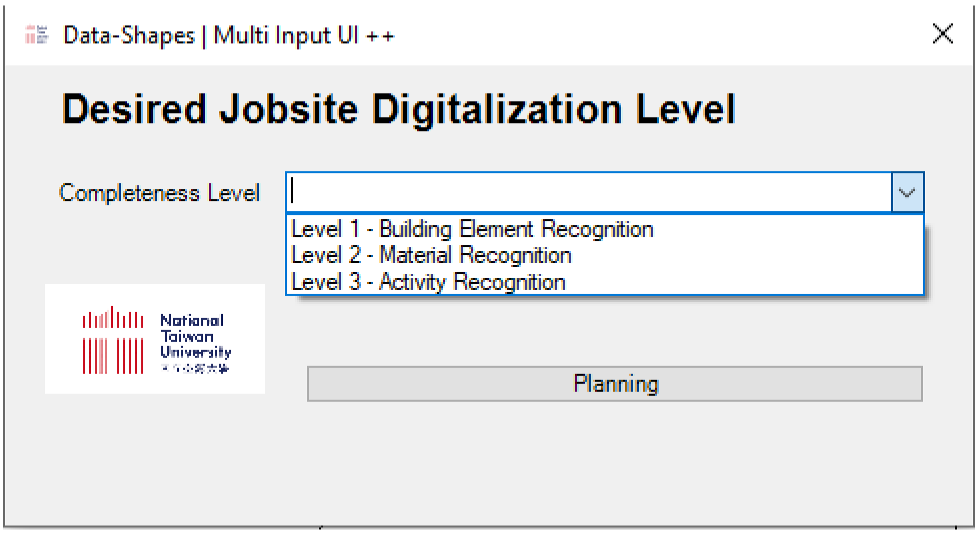
3.5.1 Jobsite Digitalization Selection User Interface

To enable project managers to easily select their desired level of monitoring, we have developed a user interface that facilitates the process. Upon running the Dynamo script, three modal windows will appear, as depicted in Figure 3.6. These modals provide a user-friendly interface for project managers to make their selections.

The first modal presents completeness levels, along with a guideline description of each level's scope and objectives. It offers insights into the recommended devices, technologies, and data acquisition methods to achieve the desired monitoring outcomes. This information helps project managers understand the different completeness level available to them. The second modal displays the specific levels of detail. Project managers can choose the level that best aligns with their project requirements and objectives. The third model shows the whole category included in the BIM model. Project managers can choose specifics elements that they want to monitor by vision-based methods. This approach ensures that project managers have a clear understanding of the available options and can make informed decisions to achieve their desired level of monitoring.



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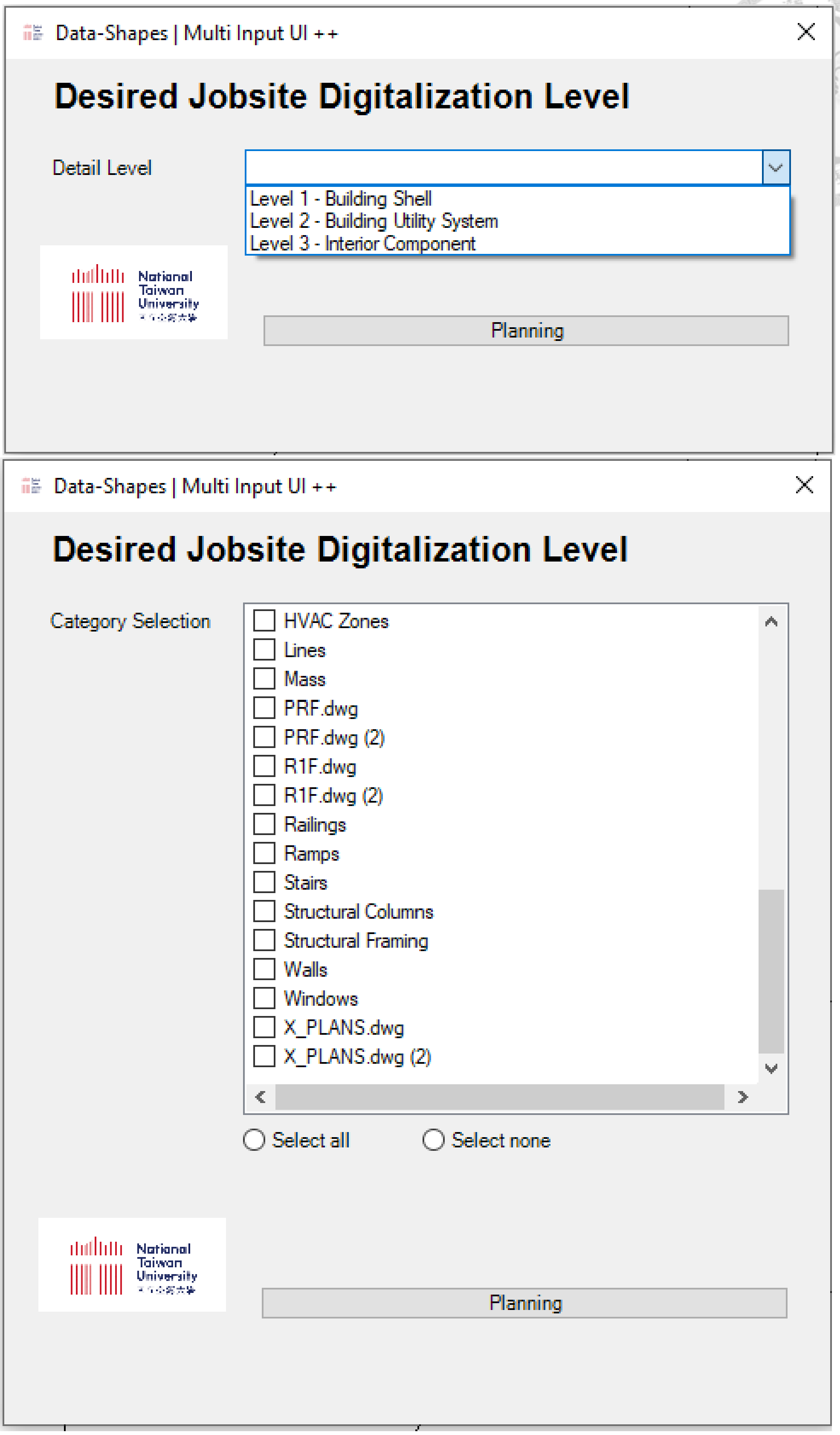

Figure 3.6: Jobsite Digitalization Selection User Interface

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3.5.2 Export Summary Report

The summary report serves as a comprehensive document that provides essential information about the monitoring process. It includes general project details, monitoring objectives, the selected methods and technologies to be used, as well as information about the elements to be monitored. Figure 3.7 shows the content of summary report.

SUMMARY REPORT	
General Information	
Project name	
Project address	
Client name	
Monitoring Objectives	
Level of completeness	
Level of detail	
Monitoring elements	
Vision-based Monitoring Methods	
Data type	
Device	
Technique	
LOD of BIM model	
Element Information	
Number of elements to be monitored	
Number of monitored elements	

Figure 3.7: Summary Report Template

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3.5.3 Export Detail List

The taxonomy is imported from an Excel sheet and utilized to extract the necessary information into a detailed list, taking into consideration the level of digitalization at the jobsite. At level 1, the detail list includes element IDs, categories, UniFormat codes, and element positions. At level 2, the list expands to include the names of material layers, as defined by MasterFormat. At the highest level, the monitoring objectives are the entities present at construction sites, encompassing the activities and resources required to create specific elements. Consequently, the detail list displays the actions and resources sourced from RS Mean. An example of the detail list can be found in Table 3.8.

Element ID	Base Level	Assembly Code	Assembly Description	Work Result Code (if Level 2, 3)	Work Result Description (if Level 2, 3)	Material (if Level 2)	Action (if Level 3)	Resources (if Level 3)	Recognized by Vision-based methods
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 11 13	Structural Cast-in-Place Concrete Forming	Wood	Install	Worker	

Figure 3.8: Detail List Template

The detail list plays a crucial role in facilitating the integration of visual sensing technologies for construction project monitoring. By incorporating essential information about each element, including its type, position, and unique element ID, the detail list provides project managers with an overview of the monitored elements.

The detail list allows project managers to easily identify and locate specific elements within the BIM model. Visual sensing technology may precisely capture and follow the progress of individual elements by tying each element to its own element ID and location on the construction site.

The detail list acts as a label table or a key reference for the computer vision system

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during the next stage of using visual sensing technologies for recognition and monitoring. As the computer vision algorithms process the visual data captured by visual sensors, the detail list identifies and categories various building elements, materials, activities, and resources on the construction site.

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Chapter 4 Implementation and Validation

This section is dedicated to operationalizing the framework introduced in Chapter 3. The primary aim is to evaluate the framework's efficacy by implementing it in a real-world context and soliciting expert feedback. Initially, the framework's application on a Building Information Modeling (BIM) model is carried out during the project's implementation phase. Subsequently, the framework and the results obtained from the implementation phase are shared with the experts who were involved in the project. Finally, the experts' perspectives are discussed and deliberated upon.

4.1 Implementation

The proposed framework was validated through a case study conducted on a building project at National Taiwan University. In the construction planning phase, the design team must ensure that the model includes adequate information to define an instance element that can be visually recognized during the construction stage. This process is further explained in the initial subsection. Subsequently, the procedure for exporting the monitoring plan is described, then presenting both a summary and detailed reports.

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4.1.1 Pre-processing Model

In order to implement the framework, there are some prerequisites information should be included in the BIM model.

- We must ensure that the element IDs are extracted from the model. Figure 4.1 shows the element ID belongs to an instance of basic wall.

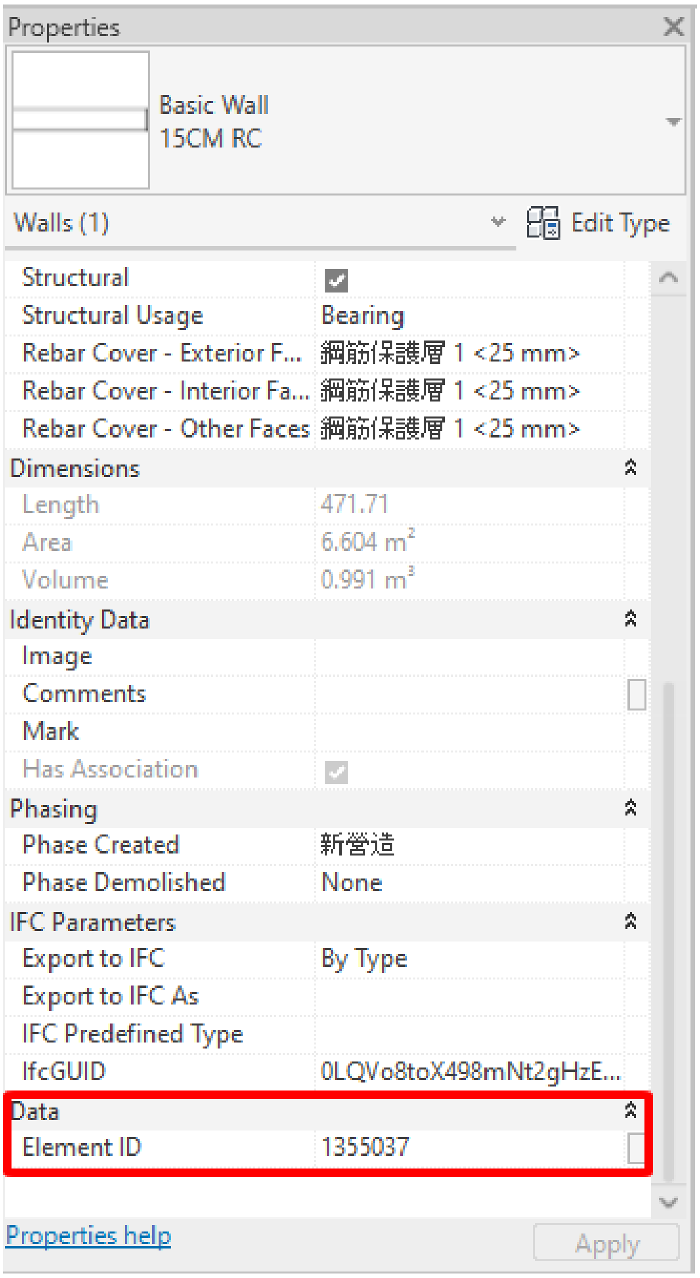

Figure 4.1: Set element IDs

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- It is necessary for each element to possess its own Assembly Code, which serves to categorize the elements. The Assembly Code in Revit is created based on the UniFormat. Specifically, in this study, we focus is on pre-processing the structural elements, whereby the assembly code is assigned solely to these elements. Figure 4.2 shows the information that included in an element.

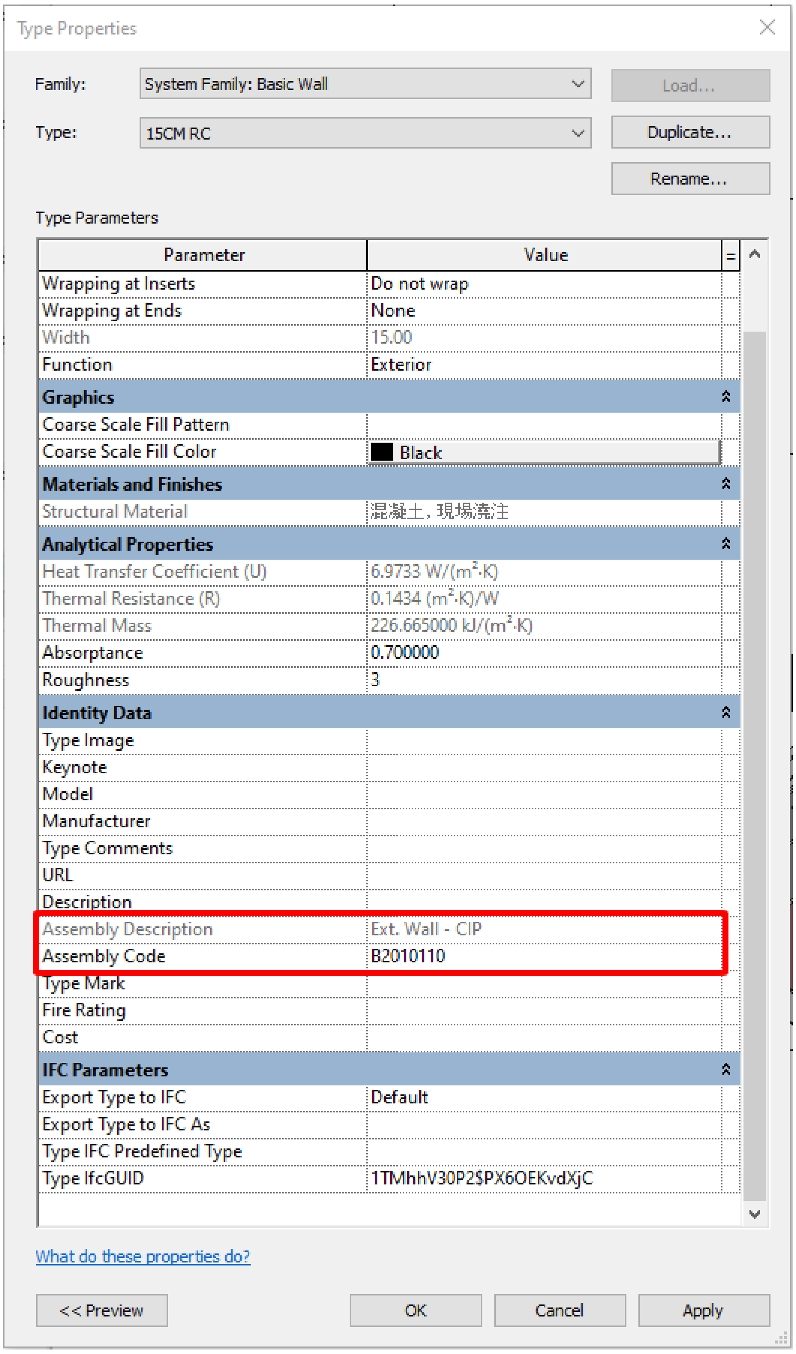

Figure 4.2: Set assembly code

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4.1.2 Jobsite Digitalization Levels Selection

During this stage, the project manager selects suitable degree of digitalization for their jobsite, in accordance with their specific requirements. This selection process is facilitated by consulting the information presented in Table 1 and Table 2. Furthermore, the project manager determines the specific elements to be captured through data acquisition methods by referring to the details provided in Table 3 and Table 4. The outcomes of this process are automatically generated by Dynamo Script. The overall implementation process of this framework is depicted in Figure 1, which offers a comprehensive overview of the steps involved in the selection of the appropriate level of jobsite digitalization and the definition of the specific elements to be monitored.

The implementation process of the framework commences by accessing the BIM model within the Revit platform and ensuring that it contains the requisite data for vision-based monitoring. The user then navigates to the ”Manage” tab in the taskbar and activates the Dynamo Play button. Next, they select the Dynamo file titled ”Vision-Based Monitoring Planning” and initiate the framework by clicking the run button. Consequently, a guideline materializes, elucidating the level of digitalization on the construction site and delineating the procedure for employing vision-based techniques. This guideline furnishes the user with essential instructions. Concurrently, the initial modal for completeness level emerges, enabling the user to make sequential choices based on their preferred plan, encompassing steps 4 to 9 as stipulated in the framework. Once the selections for completeness level have been made, the framework automatically generates a summary report and a detailed list, offering a comprehensive overview of the monitoring objectives and the specific elements to be monitored through vision-based approaches.

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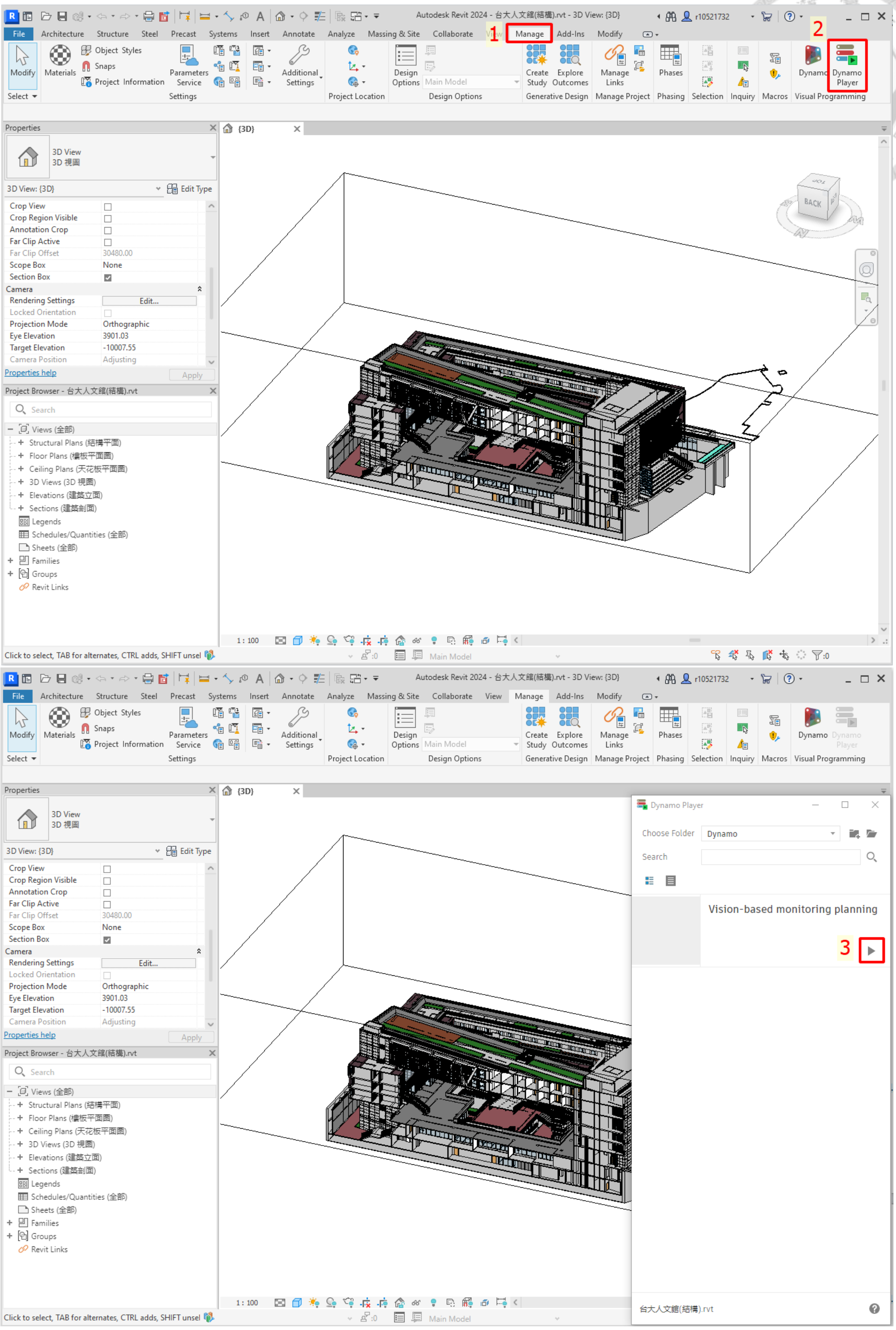

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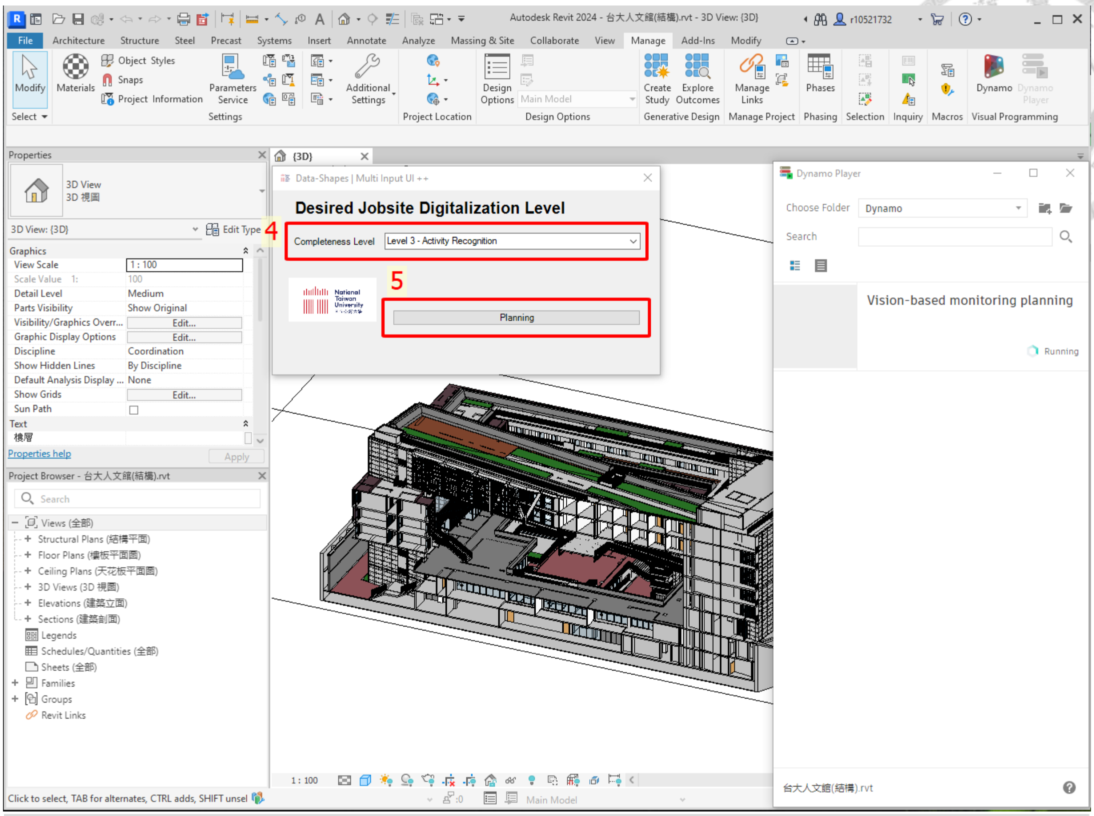

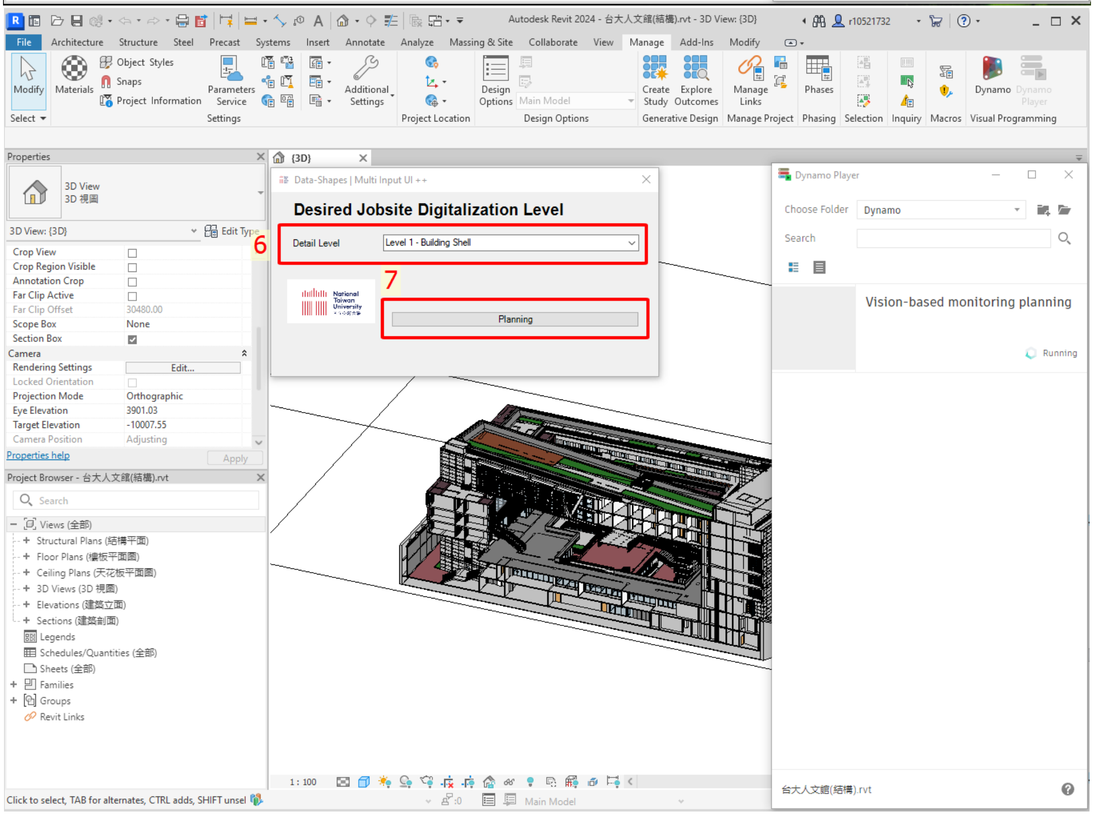

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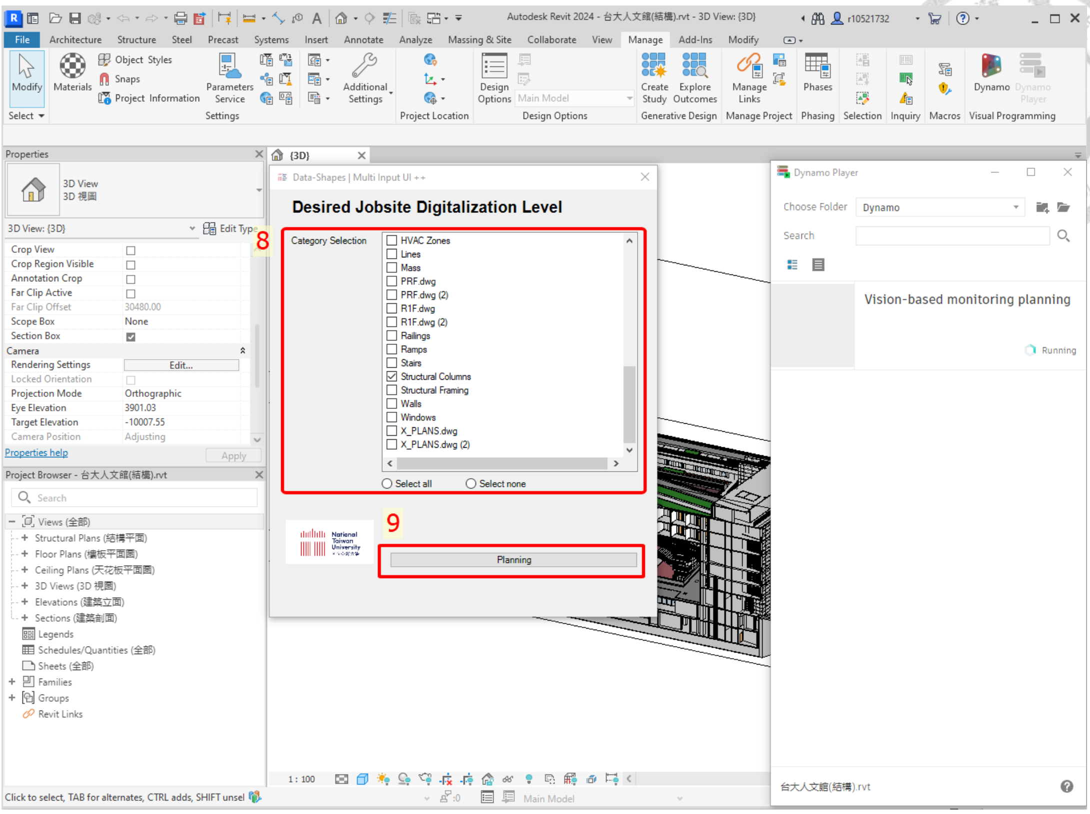

Figure 4.3: Selection Procedure

4.1.3 Summary Report and Detail Report

After selecting the desired jobsite digitalization, the summary report will automatically be exported. Figure 4.4 shows the report exported from the case study's BIM model. The general information is exported from the BIM Model project information. The monitoring objectives are defined based on jobsite digitalization levels that the project manager imported. The report shows vision-based monitoring methods: data type, device type, technique, and requirement of the BIM Model.

In this project, the project manager selects level 3, which focuses on activity recognition, specifically for monitoring the building shell, particularly the structural columns. To achieve this, the required visual data to be collected is depth video, which provides additional depth information for activity analysis. The recommended device for capturing

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this data is a video camera equipped with a depth sensor, allowing precise measurements. The technique utilized for the data analysis is the pose detection algorithm, which enables the recognition and tracking of human activity in relation to the structural columns. Additionally, to support this level of monitoring, the BIM model should have a level of development (LOD) of 300, which includes detailed information about the material layers of the building elements. In the element information section,

	A	B
1	**SUMMARY REPORT**	
2	**General Information**	
3	Project name	專案名稱
4	Project address	在此輸入地址
5	Client name	擁有者
6	**Monitoring Objectives**	
7	Level of completeness	Level 3 - Activity Recognition
8	Level of detail	Level 1 - Building Shell
9	Monitoring elements	Structural Columns
10	**Vision-based Monitoring Methods**	
11	Data type	Depth Video
12	Device	Video Camera with Depth Sensor
13	Technique	Pose Detection Activity Recognition
14	LOD of BIM model	BIM model LOD300
15	**Element Information**	
16	Number of elements to be monitored	117
17	Number of monitored elements	

Figure 4.4: Summary Report

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In this case study, the generated reports showcase the results obtained from the BIM model based on the chosen level of jobsite digitalization by the project manager. Figure 4.7 represents the detailed report for level 3, which focuses on activity recognition. The other two images, Figure 4.5 and Figure 4.6 illustrate sample reports for the lower levels.

For level 1, the report includes essential information such as the element ID, base level (position of the elements), assembly code, and assembly description (Uniformat code). For level 2, the report expands to include the work result code and description, which are extracted from the element and activity taxonomy . Additionally, the report provides the name of the task and the material layers associated with the elements. For level 3, the report goes further by exploring the actions and resources required to complete each task. The last column of the report indicates the status of the activity monitoring, indicating whether they have been recognized successfully by the vision-based methods or not. This information is used for performance assessment.

Element ID	Base Level	Assembly Code	Assembly Description	Work Result Code (if Level 2, 3)	Work Result Description (if Level 2, 3)	Material (if Level 2)	Action (if Level 3)	Resources (if Level 3)	Recognized by Vision-based methods
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP						
364755	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP						
365122	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP						
365139	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP						
365351	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP						
365370	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP						
365391	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP						

Figure 4.5: Detail Report - Level 1

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Element ID	Base Level	Assembly Code	Assembly Description	Work Result Code (if Level 2, 3)	Work Result Description (if Level 2, 3)	Material (if Level 2)	Action (if Level 3)	Resources (if Level 3)	Recognized by Vision-based methods
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 11 13	Structural Cast-in-Place Concrete Forming	Wood			
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 21 00	Reinforcement Bars	Reinforcement Bars			
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 31 00	Structural Concrete	Concrete			
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 35 00	Concrete Finishing	Finishing layer			
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	07 10 00	Waterproofing	Waterproofing layer			
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	07 21 00	Thermal Insulation	Thermal Insulation layer			
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 24 00	Cement Plastering	Cement layer			

Figure 4.6: Detail Report - Level 2

Element ID	Base Level	Assembly Code	Assembly Description	Work Result Code (if Level 2, 3)	Work Result Description (if Level 2, 3)	Material (if Level 2)	Action (if Level 3)	Resources (if Level 3)	Recognized by Vision-based methods
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 11 13	Structural Cast-in-Place Concrete Forming	Wood	Install	Worker	
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 21 00	Reinforcement Bars	Reinforcement Bars	Install	Worker	
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 31 00	Structural Concrete	Concrete	Place	Worker/ Concrete Pump	
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 35 00	Concrete Finishing	Finishing layer	Formwork Removal	Worker	
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	07 10 00	Waterproofing	Waterproofing layer	Vertical Apply	Worker	
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	07 21 00	Thermal Insulation	Thermal Insulation layer	Vertical Apply	Worker	
364472	Level(Name=B2F, Elevation=-750)	B1010240	Columns - CIP	03 24 00	Cement Plastering	Cement layer	Plaster	Worker	

Figure 4.7: Detail Report - Level 3

4.1.4 Interact the results with BIM models

- The element parameter within the BIM model includes information about the required activities and resources for each building element. By leveraging this data, project managers can automatically create a task schedule. This integration streamlines the scheduling process and ensures that all necessary activities and resources are accounted for.

- The guideline explaining the jobsite digitalization level is dynamically shown when the Dynamo script is executed. This means that as the script runs, project managers

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and stakeholders are presented with a clear understanding of the current digitalization level achieved on the jobsite.

- During the monitoring process, the point cloud with the detection results and information of the completed elements generated by visual sensing technologies, such as photogrammetry, is registered with the BIM model. This registration involves aligning the point cloud data with the BIM model's geometric representation, providing a spatial reference.

4.2 Validation

The validation process was carried out by interviewing three experts who have direct involvement in the project. The primary aim of the validation process was to evaluate the competency of the framework component. During the validation rounds, open-ended interviews were utilized as the chosen method due to their inherent flexibility. Open-ended interviews allowed for adaptable discussions tailored to the expertise of each participant, ensuring that the conversation delved into the specific areas of interest related to the framework components. The use of open-ended questions provided an opportunity to gather detailed feedback, insights, and opinions from the participants, enabling a comprehensive assessment of the framework's effectiveness.

The interview procedure consists of 4 parts, namely the introduction of the framework objectives, inquiries about personal background, practical demonstrations involving the utilization of the framework to generate automated reports, and competency-based questions.

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1. Introduction of the framework objectives: We provided experts briefly about the objectives of this study and the overall knowledge related to vision-based monitoring.

2. Inquiries about personal background: Inquiries regarding personal background were conducted in two stages. Initially, the experts were requested to provide details regarding their personal information, including company affiliation, job title, and professional experience. Subsequently, the experts were asked a series of basic questions related to the domain of visual data capture. These questions were designed to assess their fundamental knowledge and understanding of the subject matter. The questions are presented below:

   - Can you describe quickly your current process of monitoring progress on your project's construction sites?
   - Do your project management team use the camera for monitoring construction project progress?
   - Do your organization plan to adopt the vision-based monitoring methods to monitor construction project automatically?

3. Practical demonstrations: In our study, we presented the components of the framework that we developed, as well as the levels of digitalization on the construction site. Additionally, we demonstrated the reports extracted from the Building Information Modeling (BIM) model. Furthermore, we executed the Dynamo script based on the input from industry experts and showcased the outcomes derived from the BIM model.

4. Competency-based questions: Experts were presented with a set of competency

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questions to evaluate the effectiveness of the framework. These competency questions were designed to assess various aspects of the framework, such as its usability, comprehensiveness, practicality. The experts were asked to provide their feedback, opinions, and evaluations based on their expertise and experience in the field. This part starts with a set of questions including:

- Do you find this process is useful for understanding the potential of using vision-based monitoring methods?
- Do you find the reports which are exported from BIM model is meaningful for monitoring process?
- Do you have any other comments to improve the competence of this process?

More information of the participating experts can be found in Table 4.1.

Table 4.1: The interviewee's information

No	Background company	Role	Experience (years)
1	Contractor	Project manager	21
2	Contractor	AI engineering	2
3	Contractor	Safety manager, Site manager	19

During the interview, the interviewee was given the opportunity to lead the conversation and provide answers to questions through discussion. The duration of the meeting typically lasted for one hour. The interview began by discussing the current methods employed to monitor construction progress on their sites. Presently, there are multiple approaches in place for this purpose. Firstly, an information management system has been implemented to track and display the progress of the project. This system provides updates on various aspects of the construction. Another immediate method being utilized is

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the LINE group report, which offers real-time updates on the scheduled progress and the actual progress achieved each day. This allows for a daily overview of the ongoing construction activities. Additionally, weekly business meetings are held to conduct progress reviews. These meetings serve as a platform to discuss and evaluate the progress made during the week. Furthermore, a monthly project meeting is conducted specifically to monitor the progress of the construction site. This meeting provides an opportunity to comprehensively assess the advancements made on the project. It is important to note that the progress monitoring process still heavily relies on human involvement, particularly the site engineers who manually check the images collected by cameras. While there are systems and methods in place to track and display the progress of the construction project, the actual assessment and verification of the collected images are currently conducted by the site engineers.

In terms of the competency of the framework, two out of three experts agree that the application of the framework will be effective in utilizing vision-based methods for progress monitoring. The report generated from the Building Information Modeling (BIM) model is deemed useful for providing task information that is being executed on the construction sites. However, one out of three experts expressed concerns when reviewing reports that lack camera location, capture time, and budget for utilizing vision-based methods. This expert is uncertain about the clarity of using cameras to automatically define progress in the construction stage. Additionally, the experts believe that it is challenging to adopt algorithms to track work-in-progress, and they are unsure about the efficiency and benefits that vision-based methods bring to their firm.

In addition, experts have provided further suggestions to enhance the framework. It is imperative to carefully deliberate the implementation of cameras in specific areas due

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to resource constraints. This entails devising a thorough plan encompassing the setup process, determining the optimal number of cameras to be deployed at construction sites, as well as formulating a strategy for collecting visual data in accordance with the construction schedule. Overall, the framework provide promising guideline in instructions and planning for applying vision-based monitoring methods on tracking WIP.

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Chapter 5 Conclusion

5.1 Research Conclusion

Construction sites can be particularly complicated because of different activities. Several advanced monitoring methods has been developed to facilitate the monitoring process on construction sites with many kinds of devices. Thus, the increasing trend towards advanced technologies suggests that the monitoring process will become increasingly digitized and automated. This study introduced a framework for generating a systematic visual data capture plans using BIM and construction documents. The framework first includes (1) creating a jobsite digitalization level, (2) a taxonomy for identifying objects of the monitoring process, (3) visual data capture methods for different levels. An automated process is implemented to integrate with BIM models in order to generate visual data capture plans. These plans enable construction professionals to choose suitable levels of monitoring according to their specific requirements. The results show that by implementing this framework, it is possible to further understand and apply visual sensing technologies for task monitoring and operation monitoring. The level of jobsite digitalization serves as a valuable indicator for construction practitioners to determine the areas where they can begin applying vision-based monitoring methods. By understanding the necessary level of digitalization, practitioners can identify the specific fields and tasks

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that would benefit from implementing vision-based monitoring techniques. The taxonomy plays a crucial role in this process by providing a structured framework for defining the activities necessary to create specific building elements. It allows practitioners to categorize and prioritize their monitoring efforts based on the elements and tasks involved in the construction process. Additionally, data acquisition methods are essential in guiding practitioners toward the appropriate techniques for collecting visual data. By understanding the specific requirements, such as the data type, camera specifications, and technologies needed, practitioners can distinguish the most suitable methods to capture and process visual information. Overall, the level of jobsite digitalization, combined with the taxonomy and data acquisition requirements, provides construction practitioners with valuable insights and guidance in implementing vision-based monitoring methods.

5.2 Research Contribution

This research has the potential to provide a guidance for project managers to apply vision-based monitoring methods on construction sites through systematic visual data capture plans. The contributions of this research are presented below:

1. The jobsite digitalization level based on monitoring scope is proposed. This range of digitalization levels plays a crucial role in establishing a leading index that project managers can use to evaluate and determine the level of digitalization they aim to achieve on their construction sites.

2. The taxonomy makes a valuable contribution to the identification of monitoring schedules in construction projects. By providing a structured framework and classification system for building elements and activities, the taxonomy enables project

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managers to clearly define and organize the specific objects that need to be analyzed by computer vision.

3. The framework makes a significant contribution by addressing the problem of the lack of guidelines for construction practitioners regarding vision-based monitoring methods. By providing a clear and systematic approach, the framework offers a step-by-step procedure and guidance for practitioners to understand the potential vision-based monitoring techniques in planning stage.

4. A simple method for assessing the performance of vision-based monitoring adoption in construction is proposed. It allows practitioners to evaluate the effectiveness and efficiency of implementing vision-based monitoring methods on construction sites.

5.3 Research Limitations and Future Works

Although the research has effectively accomplished its goals, there are still certain limitations that need to be addressed in future studies:

- Future studies could explore integrating other data acquisition methods, such as geospatial technologies or thermal scanners. By incorporating different technologies, the framework could be enriched and offer a broader range of monitoring capabilities.

- The study primarily focused on the structural part of the building when developing the taxonomy. It would be beneficial to extend the taxonomy to encompass other complex building components, such as electrical systems, plumbing, or interior finishes. This expansion would provide a more holistic approach to monitoring and

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facilitate a comprehensive understanding of the entire construction project.

- The study emphasized the technical aspects of adopting vision-based monitoring methods. However, it is crucial to consider other factors, such as budgetary constraints and resource availability, when proposing new technologies in construction projects. Future research could incorporate these practical considerations into the framework to provide a more realistic and feasible approach to adopting vision-based monitoring methods.

In future studies, several potential research can be implemented to address the constraints:

- A RevitAPI script should be developed to create an activity schedule automatically when clicking an element.
- Develop a comprehensive guidance framework that covers all aspects, from planning to implementation and performance assessment. This framework would provide construction practitioners with a complete roadmap for adopting vision-based monitoring methods.
- Implement the recommended data acquisition methods during the construction stage to assess the competency of visual data capture plans and make necessary adjustments or improvements.
- Incorporate resource constraints into the planning phase. Future studies should develop strategies and decision-making models that take into account the financial implications and resource requirements associated with the adoption of vision-based monitoring methods. This would help project managers make informed decisions and optimize the allocation of resources during the implementation process.

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