Doctoral Dissertation

A Framework for Workflow-Based Building Information Modelling (BIM) and Database Integration for Automated Construction Progress Reporting

（ワークフローに基づく建築情報モデリング（**BIM**）およびデータベース統合による自動建設進捗報告のためのフレームワーク）

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Abstract

In the construction industry, project progress reporting is traditionally a manual and error-prone process, involving on-site checks and data consolidation. This approach not only consumes time but also suffers from inaccuracies due to the subjective interpretations of progress among various stakeholders, leading to inefficient project management. Despite the advent of digital technologies aimed at automating data collection, the construction industry’s fragmented nature often results in isolated silos of information, particularly with data from design and coordination stages residing in specialized document management systems. Additionally, the adoption of advanced technologies remains low due to various reasons.

This research addresses these challenges by proposing a framework for the semantic enrichment of Building Information Modelling (BIM) to integrate data from various phases and information systems seamlessly. By analysing existing progress reports and databases, this study identifies key data categories for developing a system that associates data with BIM elements to automate and standardize progress reporting. The practical application of this framework is demonstrated in a piling activity using Revit 2023 and Dynamo, showcasing how document approvals and quality inspections can dynamically update BIM elements to reflect real-time progress.

Moreover, to tackle the inefficiencies in manual inspection processes, this research explores the use of Mixed Reality (MR) technology. A novel MR application was developed using the HoloLens 2 and Unity, designed to automate dimensional checks of staircase features against building regulations. This MR solution not only enhances inspection processes but also sets the stage for future integration of inspection results directly into the proposed framework to update progress metrics automatically.

In summary, this dissertation contributes a novel framework and methodology for progress monitoring that leverages existing construction data and modern MR technology, thereby improving the accuracy and efficiency of construction project management without significant additional technological investments. This integrated approach ensures that progress monitoring is not only automated but also aligned with the stakeholders’ defined metrics, paving the way for future advancements in automated inspections and progress reporting.

Preface

This dissertation is the original work by Michelle Siu Zhi Lee under the supervision of Professor Nobuyoshi Yabuki. Two journal articles and 2 international conference proceedings relate to this dissertation have been submitted or published and are listed below.

Journal articles:

1. Lee, M.S.Z, Yabuki, N., and Fukuda, T. (2024). Workflow-Based BIM and Construction Data Integration for Automated Construction Progress Reporting. *Automation in Construction*, Under review.

2. Lee, M.S.Z.; Yabuki, N.; Fukuda, T. Scene Understanding for Dimensional Compliance Checks in Mixed-Reality. *CivilEng* 2024, 5, 1-29. https://doi.org/10.3390/civileng5010001

International conference proceedings:

1. Lee, M.S.Z, Yabuki, N., and Fukuda, T. (2023). Automated Dimensional Checking in Mixed Reality for Staircase Flight. Proceedings of the 5th International Conference on Civil and Building Engineering Informatics (ICCBEI2023), 557 – 564.
    - ICCBEI 2023 Best Paper Award.

2. Lee, M.S.Z, Yabuki, N., and Fukuda, T. (2023). Mixed Reality Application for Staircase Inspection. Proceedings of the 12th International Structural Engineering and Construction (ISEC12). https://doi: 10.14455/ISEC.2023.10(1).CON-24

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It has been an interesting journey that undeniably stands as among the most transformative experiences of my life.

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Chapter 1
Introduction

1.1 Background

In construction projects, project progress is required to be regularly presented in several documents, including progress claims for payment, the project schedule for overall progress monitoring, and progress reports used as written updates complementing the project schedule. The frequency and type of reported data depend on the client's requirements and contractual obligations. These data include progress updates across the design, coordination, construction, and handing-over stages that are submitted as daily, weekly, bi-weekly, or monthly reports (Sami Ur Rehman, et al. 2023). Although regular reporting is required, cost overruns and late delivery of projects are still prevalent (Josephson and Hammarlund 1999, Sami Ur Rehman, et al. 2022), highlighting that project progress reporting and monitoring is one of the key challenges the construction industry faces. This can be attributed to the lack of standardisation of project management practices (Ali and Kidd 2014) and the lack of a common understanding of what constitutes progress among stakeholders (Changali, Mohammad and van Nieuwland 2015). Additionally, largely manual methods of obtaining progress data in current practices result in inaccuracies in obtaining information for effective project control (Hasan and Sacks 2021, Omar and Nehdi 2016, Ekanayake, et al. 2021). Not only are such methods of reporting progress time-consuming (Tuttas, et al. 2015) and subjective, but a substantial amount of time spent reviewing and consolidating data from the paper-based documentation to be presented in reports also results in a continual latency when assessing a project's progress (Cox, Perdomo and Thabet 2002).

In recent years, advancements in technology that enable Automated Construction Progress Monitoring (ACPM) were demonstrated to be feasible, offering information with reduced human error and latency compared to traditional reporting methods. These technologies primarily involve the use of vision-based analysis of as-is conditions, which use either occupancy-based or appearance-based reasoning to infer progress (Yang, et al. 2015). Many of these technologies have also been made commercially available in recent years, yet the adoption rate remains low (Hasan and Sacks 2021) with one of the key reasons being the lack of standardization and collaboration due to the fragmented nature of the construction industry (Sacks, et al. 2020). While technology has progressed to the point where tools are available to automate progress monitoring, the lack of integration between technology and reporting systems causes ACPM to appear contradictory to the idea of automation since the creation of progress reports still requires manual data entry of progress percentages that were generated by technologically-advanced equipment.

Other researchers have identified other factors that contribute to the slow adoption of ACPM technologies. These include the lack of skilled personnel with knowledge of technological applications (ElQasaby, Alqahtani and Alheyf 2022, Gamil, Alhajlah and Kassem 2023, Turkan, et al. 2012), the lack of awareness of advanced tools for project monitoring (Sami Ur Rehman and Tariq Shafiq 2022), the primary audience of research studies being the academic community rather than construction professionals (Mostafa and Hegazy 2021), the nature of contracts not allowing for the integration of technologically advanced techniques into existing practices (Sami Ur Rehman, et al. 2023), and the tendency of available offerings for progress tracking to focus on modular solutions that limit its ability to meet the practical needs of construction professionals (Hasan and Sacks 2023). Hence, to increase the adoption of ACPM among construction professionals, an accessible methodology requiring minimal human intervention from the generation of progress data to final progress reporting is essential.

Building Information Modelling (BIM), as an integrating technology that offers an information structure independent of organizational barriers within projects (Sacks, et al. 2018), has a database infrastructure that allows it to capture data across various sources. Furthermore, its geometrical representation of construction elements facilitates the visualisation of workflows (Sacks, Radosavljevic and Barak 2010). Progress data generated from various sources could potentially be associated with BIM elements, producing a construction digital twin that may be used for final progress reporting. Additionally, the increasing maturity of BIM in the industry presents a unique opportunity for integrating such information to enable comprehensive automated progress tracking without the use of complex technologies. While current research in ACPM is predominantly focused on external data acquisition technologies for gathering as-is data (Kopsida, Brilakis and Vela 2015), there exists significant potential in leveraging inherent data from existing construction processes, such as site inspection data (Hamledari, Azar and McCabe 2018), and pre-construction data, such as design submissions records. These sources, especially preconstruction data, have not been considered in other automated construction project monitoring research despite containing progress information typically required for reporting. The traditional approach for preparing progress reports relies heavily on human intervention to consolidate data, as presented in Figure 1. Hence, this study proposes a framework for integrating BIM with construction documentation information collected across project stages for both element-level and activity-level progress reporting. This is achieved by semantically enriching BIM with workflow information obtained by analyzing actual construction documentation data. BIM may then be used to visualize and calculate progress using the available inherent element quantities. Additionally, an automated approach to performing quality inspections is introduced within the same framework to streamline the production of inspection records, thereby enhancing efficiency and accuracy. A comparison of the proposed approach against the conventional approach is presented in Figure 1.

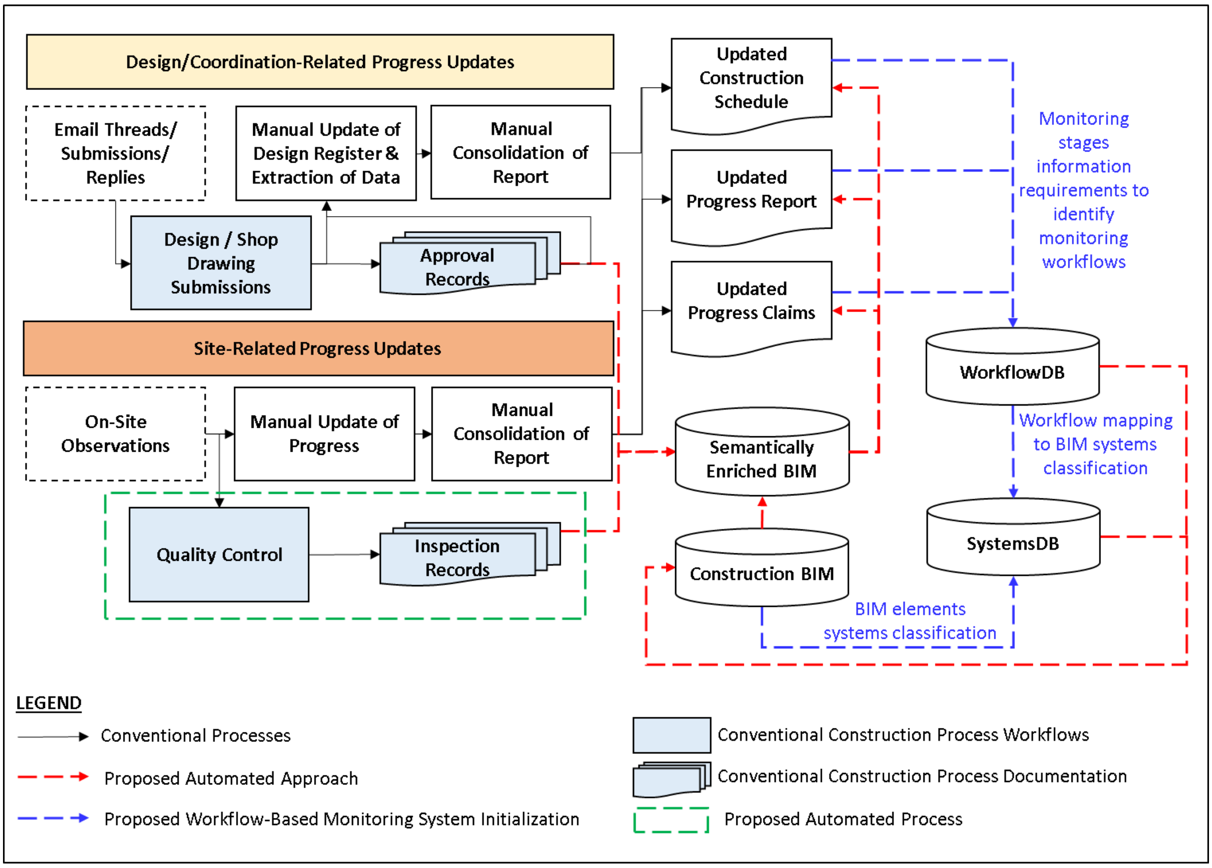


Figure 1. Overview of the proposed research

1.2 Problem statements and research gap

Following the introduction above, several problems exist that hinder the adoption of ACPM, impeding the efficiency of construction progress reporting. They can be summarized as follows:

(1) Despite the evolution of construction technologies that are available commercially, their minimum-viable-approach solutions often operate as isolated solutions, not meeting the needs of construction professionals.
(2) There is currently a non-standardized way of assessing a project's progress, leading to inconsistencies among stakeholders when assessing a project's progress.
(3) Despite the current availability of ACPM solutions, the industry lacks the required skills to implement these solutions due to the complexity and specialist knowledge required. This results in the predominance of paper-based data-gathering processes, leading to the accumulation of unstructured data and impeding automation efforts.
(4) Current ACPM solutions rely on vision-based technologies and analysis, which requires large datasets for model training. These solutions also encounter challenges, such as occlusion issues arising from the dynamic environments of construction sites. Furthermore, they do not address the demands of construction progress reporting, thereby not aligning with the practical requirements of construction professionals.
(5) With increasing maturity in the use of BIM and Common Data Environments (CDEs), availability of structured data that contains information about a project progress becomes increasing available. This data can be leveraged and seamlessly integrated with BIM to infer progress. However, it is essential to address existing limitations to ensure that the outcomes of such automation can be effectively integrated into a comprehensive framework for progress reporting.
(6) The current research on ACPM fails to address an essential step integral to the construction process: inspections. Hence, there is a need to explore technologies capable of conducting inspections autonomously, such as automated dimensional checks, which are a routine aspect of inspections. Moreover, the resulting data from these inspections must be compatible with an overarching framework to ascertain a project's progress accurately.

Given the challenges highlighted, it is necessary to develop an integration framework to establish a standardized comprehension of a project's progress across various stakeholders. This framework should be able to facilitate information interoperability among diverse construction technologies or platforms, with BIM as the central integral technology. Additionally, further research should also be done to address limitations identified in the use of technology that concerns digital inspections, with a particular emphasis on the collection of structured data.

1.3 Research objectives

BIM has the potential to address many of the challenges in construction progress reporting by providing a centralized, visual, and standardized platform for data integration, real-time updates, and collaboration. Its ability to bridge the gap between specialized trades, manage complex project data, and reduce information silos makes it a valuable tool for improving the accuracy and consistency of progress reporting in construction projects. Hence, this research proposes a framework to extend the capabilities of BIM via semantic enrichment. Additionally, it explores the feasibility of using technology for automated inspection to leverage these findings for integration into the framework. This research aims to achieve the following:

(1) To identify the information required for progress reports and to standardize information types so that it can be collected in a structured manner suitable to automate progress reports.

(2) To develop a framework for semantic enrichment of BIM to facilitate the integration of data from various construction technologies and platforms.

(3) To develop an automated digital inspection methodology, particularly utilizing Mixed Reality (MR) technology, a potential technology that has both the hardware and software that could automate inspections with results that could be used to be integrated into the framework.

The developed framework and automated inspection prototype shall then be tested in real-world scenarios to validate their practical applicability.

1.4 Research significance

The significance of this research lies in its potential to improve construction progress monitoring and inspections through the application of advanced BIM techniques and innovative MR technology. The proposed methods benefit construction professionals by reducing the time required to produce progress reports, leveraging mature technology and existing construction data to achieve automated monitoring without requiring highly technical solutions. Additionally, this research provides a standardised monitoring system by using actual project documentation to determine the granularity of design, fabrication and installation activities required for practical reporting. This standardization is also valuable for the academic community. Offering a foundation for defining categorization criteria for construction progress. Since the proposed methodology relies on existing construction data for inferring progress, the inherent subjectivity associated with inspectors' judgements should be addressed. Thus, this research seeks to explore the extent to which MR technology can mitigate such subjectivity, thereby enhancing the reliability of the proposed automated construction progress monitoring system. For the research community, the proposed methodologies are pertinent for further refinement of automated inspection solutions where results can be integrated into overarching frameworks for inferring progress more accurately and systematically. This research thus contributes to both practical applications in the construction industry and theoretical advancements in construction management and technology.

1.5 Overview of dissertation

This dissertation consists of six chapters as follows:

Chapter 1 Introduction

This chapter dictates the background and research objectives that substantiate the purpose of this research.

Chapter 2 Literature Review

This chapter provides an overview of past research relating to current practices in construction progress monitoring. It delves into the current state of automation in construction progress monitoring and provides insights into the present state of semantic enrichment of BIM. Additionally, it explores other research for digital inspections, particularly those employing MR technologies, and how technologies have been used for dimensional inspections.

Chapter 3 Workflow-Based BIM for Construction Data Integration

This chapter explores the information required to be presented in periodic progress reports by evaluating the actual project reports of two projects located in Singapore to attempt to define what type of data is required to be collected so that automated progress reports can be enabled and presents the proposed framework for tracking construction progress using data that is generated from construction processes. Subsequently, the framework is applied to a piling activity of an actual project to validate the framework. A discussion of the result is then presented.

Chapter 4 Bridging Automated Inspections for Automated Progress Monitoring

This chapter provides an in-depth discussion of the limitations and potential of current inspection methodologies in the construction industry. It highlights the challenges of manual inspections, including subjectivity, inconsistency, and the lack of standardization, which can lead to inaccuracies in progress monitoring within the WBPMS framework, since statuses of inspections are used to determine progress. It assesses MR's potential for automated real-time inspections. The discussion sets the stage for exploring the feasibility of MR in automating dimensional checks.

Chapter 5 Mixed Reality Inspection Automation using Scene Understanding

With the proposed framework established in Chapter 4, this chapter delves further into the intricacies of digital inspection. The feasibility of utilizing MR as a digital inspection tool is investigated for a particularly tedious task, the inspection of a staircase flight, where conventionally, each flight's riser height, width and headroom has to be measured individually for dimensional compliance checks. Such digital inspection methodologies would serve as a stepping stone to form a seamless integration of digital inspection statuses into the framework to enable automated progress monitoring. The development of an MR application to achieve automated dimensional checks is documented, and an experiment was done by volunteers from the construction industry to compare the results obtained by different volunteers using MR and conventional tools. Subsequently, results are analysed and discussed.

Chapter 6 Conclusion

This chapter summarizes the conclusion of the study and contributions of this research and then provides recommendations for future improvements.

Chapter 2
Literature review

2.1 Introduction

This thesis focuses on the development of a framework to enable automated construction progress monitoring using inherent construction data, the state of construction progress monitoring and reporting methods in the construction industry, technologies that have been investigated for automation of progress monitoring, the state of semantic enrichment of BIM, as well as technologies that enable automated digital inspections are review in this chapter as shown in Figure 2. A summary is included at the end of this chapter.

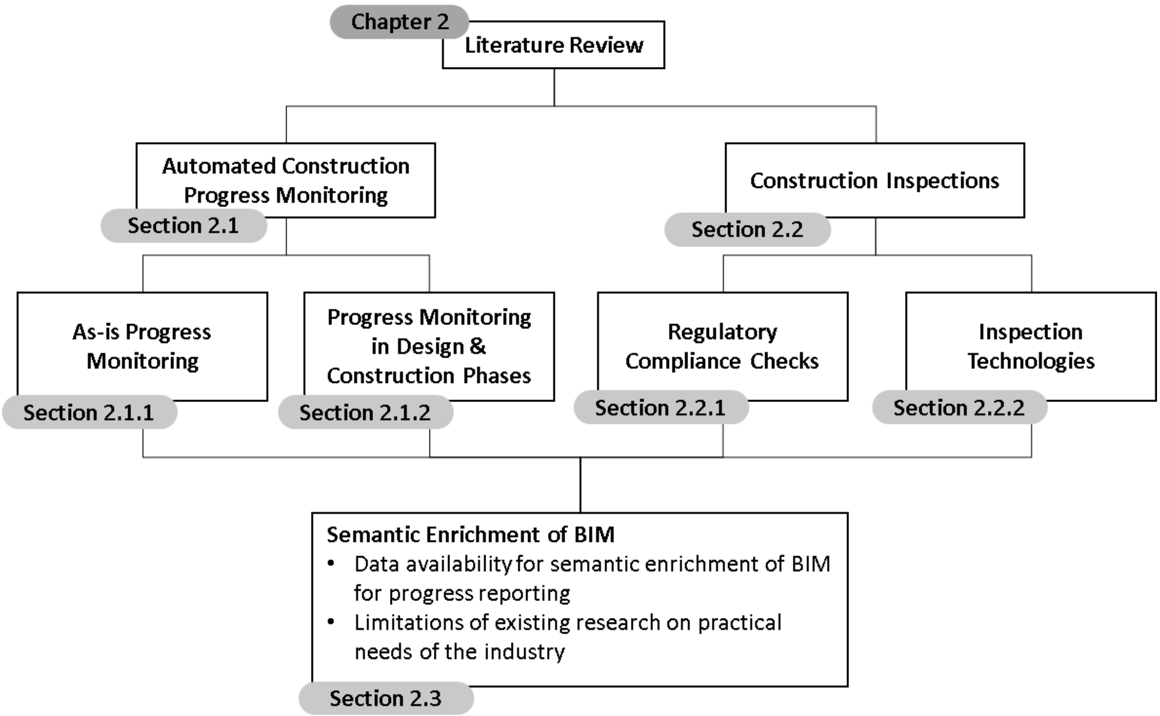


Figure 2. Overview of literature review

2.2 Automated construction progress monitoring

2.2.1 As-is progress monitoring

Research on construction progress monitoring before 2007 primarily revolved around conventional practices that relied heavily on manual data collection at construction sites. Subsequently, there has been a notable shift in research focus towards digitalization and automation, with BIM emerging as a prominent subject of study in this field (Patel, Guo and Zou 2022). Despite substantial research efforts, a field survey conducted among construction personnel in 2021 confirmed that the majority of respondents still depended on traditional paper-based reports for data gathering through physical site visits, although commercial applications of technologies have become increasingly available (Hasan and Sacks 2021). These applications use technology to collect on-site information that includes workers and equipment count (Echol Tech Pte Ltd 2022, PYLONAI 2022), the use of Artificial Intelligence (AI) to analyse video camera feeds for safety hazards identification (Invigilio 2021) or for counting construction equipment that enter or exit a construction site (Evercam 2022). The use of drones to produce a photogrammetry model that contains sufficient details for earthwork measurements can also be easily achieved (DroneDeploy 2023). 360° images or videos to capture as-built site conditions have also been gaining traction. These images can be used for visual comparison against a design BIM (Airsquire 2021, StructionSite 2022, Cupix 2022, HoloBuilder 2023). Some innovators have also further developed capabilities that could analyse the 360° images to automatically determine the progress completion of specific trades (OpenSpace 2023) or to compare as-built conditions against design BIM to determine progress completion (Buildots 2022). However, data on the accuracy of the progress detection is not available publicly to the best of the author’s knowledge. While specific limitations still exist in many computer vision applications due to limited training datasets or occlusion issues, cutting-edge research, such as utilizing synthetic images as training datasets, is being conducted to improve this technology (Núñez-Morales, et al. 2023).

Another study highlighted that in cases where manual data gathering was not employed, construction progress monitoring frequently relies on remote sensing technologies to determine progress by using image processing or laser scanning methods, which are then compared against 3D or 4D BIM to give results of high reliability (ElQasaby, Alqahtani and Alheyf 2022). This observation aligns with the commercially available offerings mentioned earlier in the preceding paragraph. Nevertheless, the high costs of adopting these technologies hinder widespread adoption in the industry (Turkan, et al. 2012).

Presently, implementation of construction technologies on-site for monitoring is primarily focused on functions such as comparing the as-built against the as-planned conditions, real-time site monitoring, and digital information projection (Hasan and Sacks 2023). These methods of construction progress monitoring often involve using data acquisition technologies, such as geospatial data collection via Global Positioning Systems (GPS), Ultra-Wide Bandwidth (UWB), Radio Frequency Identification (RFID) or barcodes, digital imaging using laser scanners, cameras or unmanned aerial vehicles. Subsequent data post-processing is conducted to determine the state of construction (Gamil, Alhajlah and Kassem 2023). Kopsida et al. (2015) conducted a comprehensive review of current automated progress monitoring methods utilizing laser scanning, digital imaging, and videos as data acquisition technologies. The authors noted that these methods are not yet fully effective in assessing progress in indoor environments, which often involve computationally expensive data post-processing with results frequently lacking in object-related information.

Despite the technological advancements and the introduction of various digital tools aimed at enhancing the accuracy and efficiency of progress monitoring, challenges such as high costs, adoption rates, and technological limitations persist. Continued research and development into overcoming these obstacles, alongside increasing the accessibility of these technologies, are crucial for the widespread implementation of effective and precise construction progress monitoring systems.

2.2.2 Progress monitoring in the design and construction phases

Research on the application of BIM for progress monitoring during the design and coordination phases is scarce despite its considerable impact on the subsequent construction phase. Instead, this monitoring aspect is often explored within the distinct construction supply chain management domain. Le et al. (2022) highlighted the operational challenges in integrating BIM with construction supply chain management, emphasizing the need for process standardization to improve supply chain integration. This observation underscores the importance of progress monitoring not just in the construction phase but also in the design and coordination phases to ensure seamless progress monitoring across all stages of construction.

On the other hand, Jang et al. (2022) demonstrated the effectiveness of a proprietary BIM-based management system in tracking the progress of precast structures throughout various project phases, including design, scheduling, production, logistics, installation, and payment. Their findings suggest that such systems can significantly improve the management and planning of precast structures, indicating that similar strategies could also benefit conventional construction projects. Similarly, Getuli et al. 3D (2016) explored a method using BIM360 Glue and BIM360 Field, which enables the integration of construction properties like install and purchase dates into BIM models. This system also supports adding custom metrics such as "Construction Percentage Progress", allowing for manual progress updates from 1% to 99%, with 100% indicating completion confirmed by an authorized reviewer. This cloud-based enhances real-time progress tracking through real-time synchronization of data but faces challenges in standardizing the understanding of completion percentages among project stakeholders. Furthermore, since it relies on manual data entry of progress percentages, such progress may be subjective and result in inaccuracies.

These studies underline the potential of BIM to facilitate progress monitoring across different construction phases and the need to standardize progress assessments across the industry to enhance the efficiency of project management practices in construction.

2.3 Construction inspections

2.3.1 Regulatory compliance checks

Quality inspections are always required to ensure that buildings have been constructed in accordance to regulations and client specifications to ensure safety and functionality (Ma, et al. 2018). However, building compliance requirements for construction regulations are complex and vary significantly. An example is the dimensional specifications for staircases, detailed in Table 1. These specifications are intended to be precisely reflected in designs and followed during construction. However, unforeseen site conditions or construction tolerances may lead to deviations from the planned specifications. Therefore, post-construction inspections are crucial to ensure that the constructed features comply with the regulatory standards. These inspections help identify and rectify any discrepancies that might affect the building's safety and usability.

Table 1. Dimensional regulatory requirements

Design Parameter	**OSHA**[1]	**BS 5395-1: 2010**[2]	**Approved Document V7.03**[3]
Max. riser height	240 mm	190 mm[a]	175 mm[b]
Min. width	560 mm	1000 mm[a]	1000 mm[c]
Min. headroom	2030 mm	2000 mm	2000 mm[d]

[1] United States Department of Labor, Occupational Safety and Health Administration
[2] British Standard: Stairs, ladders and walkways – Part 1: Code of practice for the design, construction and maintenance of straight stairs and winders
[3] Singapore's Building Construction Authority Approved Document V7.03
[a] Varies depending on stair category - dimension shown is for general public stairs
[b] Heights shall be of uniform height and size, where a tolerance of 5mm between two consecutive steps in any flight of staircase is acceptable
[c] Revised in Dec 2022 from 900mm to 1000mm; Varies depending on type of building use – dimension shown is for general buildings
[d] Varies depending on space function - dimension shown is for general public stairs

In the construction industry, linear distances are commonly measured using traditional tools such as metal tape measures and surveying chains (Kattatray and Wadalkar 2021). For regulatory measurements like site boundaries and building heights, registered surveyors are mandated to use specialized equipment like total stations, which provide necessary accuracy but can be labour-intensive in indoor settings due to their requirement for line-of-sight operation (Land Surveyors Board Singapore 2022). Although total stations deliver high precision, this may not be necessary for many indoor mapping applications where laser scanners could offer a more efficient alternative despite the need for external targets and post-processing alignment (Liscio, Hayden and Moody 2016, Tang, et al. 2010). Nonetheless, tape measures remain prevalent in the industry due to the high costs and operational expertise required for sophisticated surveying instruments.

Transitioning from traditional measurement tools to advanced technologies, the introduction of devices with mobile scanning abilities offers a promising alternative. These devices, such as MR headsets, have the potential to utilize sensor data to automate dimensional checks, overcoming the limitations of line-of-sight requirements and manual errors associated with tape measures. This technology not only enhances the efficiency of post-construction inspections but also automatically supports compliance with complex building regulations, such as those for staircase dimensions, removing the need for inspectors to know regulations by memory. Furthermore, digital results from these inspections can be systematically stored in databases, facilitating easy retrieval for downstream applications and contributing to more streamlined project workflows.

2.3.2 Advanced inspection technologies

Inspections in construction, particularly during the construction stage, involve various specific trades and have recently seen innovative advancements. For instance, the use of Unmanned Aircraft Vehicles

(UAVs), coupled with computer vision technologies, has become increasingly popular for façade inspections (Motayyeb, et al. 2023, Chen, et al. 2021). This method enhances safety and precision, offering a significant improvement over traditional techniques by detecting defects that are difficult to spot with the human eye. Such technologies not only streamline the inspection process but also increase the accuracy of the assessments.

As the construction industry continues to innovate, the shift from traditional methods to advanced technologies is apparent. Following the introduction of UAVs for external façade inspections, EXtended Reality (XR) technologies are also gaining traction for inspection applications during the construction phase.

XR encompasses augmented reality (AR), Virtual Reality (VR), and MR, with MR defined as a combination of AR and augmented virtuality where both virtual and real environments are merged (Milgram, et al. 1994). A review of these technologies indicated that VR is valued for its immersive experience within virtual setups, AR supports decision-making with enhanced visualization in physical spaces, and MR uniquely integrates the immersive aspects of VR with the visualization benefit of AR, making it particularly suitable for interactive onsite applications (Alizadehsalehi, Hadavi and Huang 2020). MR has been applied in diverse fields beyond the built industry, including virtual tourism (Talwar, et al. 2023, Vargas-Cuentas, Huamani and Roman-Gonzalez 2021) (Talwar, et al. 2023, Vargas-Cuentas, Huamani and Roman-Gonzalez 2021), medical instruction augmentation (Pose-Díez-de-la-Lastra, et al. 2022, Galati, et al. 2020), educational enhancements (Kuleto, et al. 2023, Farzam, Kaiser and 2022), and heritage BIM creations (Silva and Teixeira 2020, Banfia, Brumanaa and Stangab 2019, Terrugi and Fassi 2022). Despite its successful applications, each domain faces unique challenges that underscore the need for ongoing development to harness MR's capabilities fully.

In the Architecture, Engineering, Construction, and Operations (AECO) industry, 49% of research has focused on construction phase applications like site inspections, construction simulations, training for assembly, and enhancing construction safety (Cheng, Chen and Chen 2019). Conversely, a recent study indicated a shift towards pre-construction stages in XR applications aimed at sustainable construction, emphasizing early decisions such as sustainable material selection (Li, et al. 2023). Delgado et al. (2020) also highlighted that construction companies have a high interest in investing in AR technologies. These trends highlight growing interest in utilizing XR technologies to enhance efficiency and sustainability in the AECO sector.

Furthermore, MR technologies are being explored as an alternative to traditional 2D drawings for various tasks during the construction phase. These include installations of electrical and piping services (Chalhoub and Ayer 2018, Da Valle and Azhar 2020, Hou, Wang and Truijens 2013) and construction safety applications (Moore and Gheisari 2019). Building inspections and context visualization also benefit from MR applications, allowing for more interactive processes (Machado and Vilela 2020).

Notably, Chung and Chun (2019) innovated a trade inspection process using MR to enable visual comparison of BIM with the actual construction site, paired with digital checklists to record inspection details and progress manually. Similarly, Zhou et al. (2017) and Kwon et al. (2014) have developed methods to use AR markers and glasses to compare site images with BIM elements to inspect tunnel segment displacements and identify defects, respectively. These studies suggest moving towards markerless AR systems to reduce setup times and improve efficiency.

In a different approach, Nguyen et al. (2021) developed a BIM-based MR application tailored for bridge inspections, which utilizes BIM objects to link various types of inspection data efficiently. This integration facilitates comprehensive information management throughout the maintenance phase, showcasing the pivotal role of BIM in enhancing the functionality of MR applications in inspections. The consistent reliance on BIM across these applications points to its indispensable value in the MR inspection ecosystem, though its availability can sometimes pose challenges.

These studies highlight the integral role of MR and BIM in transforming traditional construction and inspection processes. However, they also reveal a significant challenge: the segregation of construction technology into isolated information silos. This segmentation necessitates a framework that can manage and integrate data across these technologies to ensure comprehensive project management. Semantic enrichment of BIM could provide a viable solution by incorporating domain-specific knowledge, thus creating information containers that enable seamless data integration. The following section will delve into the current advancements in semantic enrichment of BIM, exploring the academic landscape and identifying gaps that need to be bridged for enhanced data interoperability.

2.4 Semantic enrichment of BIM

The recent increase in studies focusing on the semantic enrichment of BIM underscores the need to extend the schema of BIM for broader applications. Zhang and El-Gohary (2016) identified critical gaps in the Industry Foundation Class (IFC) schema, particularly in its ability to express building code requirements. Developed by BuildingSMART, the IFC schema serves as a vendor-neutral standard facilitating data exchange across building and infrastructure projects (BuildingSMART 2023). Although the IFC schema provides a robust framework for data interoperability, progress monitoring applications demand tailored semantic enhancements. Blosch and Sacks (2018) argue that different challenges necessitate distinct model enrichment strategies. Moreover, integrating additional IFC parameters to streamline progress reporting involves updating a 4D BIM and adopting a structured, task-based approach that supports diverse data collection methods (Sheik, Veelart and Deruyter 2023).

Jiang et al. (2023) analysed research trends in the semantic enrichment of BIM, noting a shift towards the use of 3D geometric modelling to enrich BIM semantically. They identified several methods for this enrichment, including semantic web technology, rule-based reasoning, machine learning, and database-based integration. Their review of 23 scientific articles revealed that integrating BIM with external databases could improve information management to support the activities of documentation, monitoring, and conservation of heritage buildings (Cursi, et al. 2022). This practice could also be beneficial for construction projects. These studies demonstrate a broadening scope of BIM applications beyond traditional uses, highlighting its potential in improving construction management processes.

The discussed studies highlight the expanding role of BIM in construction management, propelled by advances in semantic enrichment and integration with external databases. This semantic enhancement of the BIM framework, particularly through the use of advanced technologies like the semantic web, machine learning, and rule-based reasoning, not only broadens BIM's applicability in traditional fields but also extends its benefits to complex tasks such as heritage conservation and progress monitoring. Thus, it is essential to continue exploring integrative techniques to fully leverage BIM's potential in streamlining construction processes and enhancing data interoperability, ultimately leading to more efficient project management outcomes.

2.5 Summary

The literature review explores automated construction progress monitoring technologies, particularly emphasizing the pivotal role of BIM alongside various digital tools. Despite technological advancements that facilitate real-time data collection and analysis, significant challenges persist, including integration complexities, high costs, and a lack of standardization across tools and processes. Furthermore, existing technologies predominantly focus on gathering as-built data, neglecting the need to report and consolidate design and fabrication stage statuses for comprehensive progress monitoring.

Research demonstrated that BIM-based systems can enhance project management by integrating progress data across different construction stages (Jang, Son and Yi 2022). The system not only improved work processes and reduced workloads in offsite construction projects but also underscored the potential for broader application in conventional construction settings. Getuli et al. (2016) also demonstrated improved data management using BIM-based systems and digital inspections. The system introduced field-based parameters that could synchronize field inspection data back to BIM elements, highlighting the critical need for systematic methods to enrich BIM semantically. This would extend its schema to support more comprehensive applications, particularly enhancing data operability and management across the construction project lifecycle. This summary underscores the necessity of advancing integration techniques and frameworks to fully leverage BIM's capabilities in streamlining construction processes and enhancing project management efficacy.

While research has significantly advanced in automating construction progress monitoring through technologies like BIM, UAVs, and MR, a critical aspect often overlooked is the capability for conducting quality inspections. These technologies, particularly effective in capturing progress data, fall short in performing roles such as compliance checks against regulatory requirements or verifying construction against design specifications. Nonetheless, advancements in MR and UAV technologies are proving transformative for construction safety and efficiency. These tools enhance safety compliance and provide high precision during compliance checks, which is essential for quality assurance in building projects. This integration of advanced technologies demonstrates potential yet underscores the need for developments that bridge the gap between progress monitoring and quality inspections since inspections are always required after construction is completed.

Integrating inspection technologies such as MR with BIM presents a significant opportunity to enhance construction inspections and progress monitoring. Currently, research has not extensively explored edge computing for inspections that can inform progress completion metrics. The existing use of these technologies in isolation limits their effectiveness, underscoring the necessity for a unified framework that can integrate data across various platforms and construction phases effectively. This research aims to develop such a framework by semantically enriching BIM to unify stakeholders' understanding of project progress at all stages. This will include leveraging automated inspection checks statuses to complete the data loop, ensuring comprehensive project monitoring and management. The proposed methods, validations, discussions, and final conclusion will be elaborated in subsequent chapters. This approach aims to bridge the current gaps, facilitating improved data management and utilization through integrated technological solutions.

Chapter 3
Workflow-based BIM for construction data integration

3.1 Introduction

Progress information is required in project progress reports, progress claim reports, and construction schedules. Before a framework can be established, the information requirements of these reports are analysed. This chapter presents an analysis of two actual project progress reports, identifying the data and data type that was presented in past project progress reports and progress claims.

After establishing the information requirements of progress reporting, a framework for collecting the required data is proposed and validated by a piling activity in an actual project in Singapore. Various databases available from the project are analysed to extract information to automate the project progress reporting process. The process and results are detailed in this chapter.

3.2 Information requirements for progress reporting

3.2.1 Proposed approach

An initial analysis was conducted on project documentation from two construction projects in Singapore, focusing on progress claims, progress reports, and construction schedules. This analysis aimed to determine the necessary granularity and data type requirements for reporting progress on structural elements, which were categorized into foundation and structure elements. Based on the gathered information, two databases were created: the Workflow Database (WorkflowDB) and Systems Database (SystemsDB). These databases serve as the foundational framework for structured progress reporting. The WorkflowDB catalogues unique workflows which detail the substages needed to monitor progress for specific activities. These substages are identified based on the most granular details in the construction documents. The SystemsDB maps each BIM element or the system of the elements to an appropriate workflow. For example, the driven pile process typically includes substages like setting out, pile driving, welding pile connections, and hacking to the pile cut-off level. However, substages like setting-out are not typically monitored in progress reports, progress claims or construction schedules and, therefore, will not be included as a monitored stage in the WorkflowDB. The SystemsDB is required in scenarios where construction elements, such as steel and precast piles, fall under different systems classifications but follow identical workflows due to procedural similarities. This commonality allows different systems to reference a single monitoring workflow. Thus, the two databases work together to simplify the progress reporting process across different systems.

The general contractor Penta-Ocean Construction Co., Ltd provided weekly and monthly project progress reports for two construction projects in Singapore for this research. They consist of Project A, a 1,400-bed hospital comprising three 10-story buildings with two basements, excluding piling, and with a gross floor area of 288,000 m^2, completed in August 2018, and Project B, an infrastructure project that includes a 5,575 m^2 waterfront wharf supported by an 800-mm-thick cast-in-situ slab atop bored pile foundations, alongside a 43,600 m^2 staging area supported by 5,955 driven spun piles, and an approximately 5,000 m^2 single-story operations building.

3.2.2 Monthly/Weekly progress reports

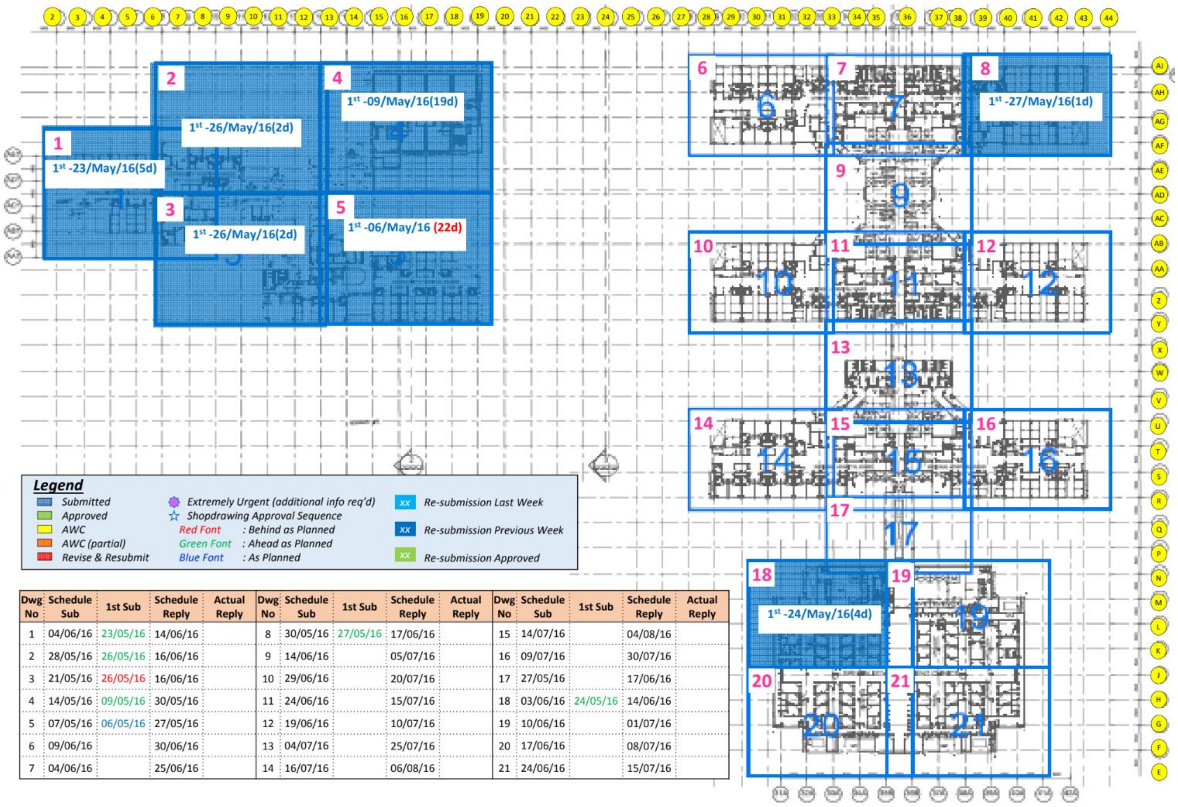
Table 2 illustrates the contents of the monthly progress reports across five main categories based on the potential source of information: project information, documentation, field information, planning information, and workplace safety, health, and environment (WSHE) information. Project information encompasses general project details such as contract award date and stakeholder information established at the project's inception. Documentation includes all formal project papers like letters, reports, and drawing submissions. Field information entails data collected on-site while planning information originates from the construction program. WSHE information specifically relates to safety and environmental data collected on-site.

Both Project A and Project B require the inclusion of similar categories in their progress reports, though their submission frequencies differ – Project A submits weekly, and Project B monthly. These reports are critical for tracking document statuses and site progress, which are essential for assessing overall project health. For instance, design progress updates are covered in Sections 11 to 14 in Project A and Sections 3.2 to 3.3 in Project B, while site progress appears in Section 2 of Project A and Section 3.9 of Project B.

Table 2. Project progress report contents

Section	Project A Weekly Report Contents	Type of Information	Section	Project B Monthly Report Contents	Type of Information
1	Project Outline	Project Information	1	Executive Summary	Project Information
2	Site Progress Update	Field Information	2	Project Milestones	Project Information
3	Three Weeks Rolling Program	Planning Information	3	Project Progress Overview	
4	Manpower and Equipment	Field Information	3.1	Status of Delay Events and Notified Claims	Documentation
5	Progress Photographs	Field Information	3.2	Authority Submission Status	Documentation
6	Forecast of Activities	Planning Information	3.3	Status of Design Review	Documentation
7	Environmental Health Safety (EHS) /Public Complaints Report and Status		3.4	Status of Confirmation of Direction	Documentation
7.1	EHS	WSHE Information	3.5	Superintending Office's Instruction (SOI)	Documentation
7.2	Public Complaints	WSHE Information	3.6	Quotation Submission	Documentation
7.3	Noise Level Reports	WSHE Information	3.7	Status of Variation Orders (VOs)	Documentation
8	Site Memo Record and Status	Field Information	3.8	Exceptional Weather Information	Field Information
9	Authorities' Visitation Record and Status	Field Information	3.9	Monthly Meeting Presentation	Field + Planning + Documentation Information
10	SOI Record and Status	Documentation	4	Site Progress Overview	
11	Shop Drawing Submission (SDS) Summary and Status	Documentation	4.1	Major Site Activities	Planning Information
12	Request for Information (RFI) Summary and Status	Documentation	4.2	Workplace Safety & Health (WHS) Statistics and WSH & Environment (WSHE) Activities	WSHE Information
13	Request for Approval (RFA) Summary and Status	Documentation	4.3	Quality	Field Information
14	Authorities Submission/Approval Record and Status	Documentation	4.4	Manpower and Resources	Field Information
15	Organization Chart	Project Information	4.5	Site Photographs	Field Information
16	Schedule of Meetings	Project Information	5	Key Issues	Project Information
17	List of Contractors and Suppliers	Project Information	6	Outstanding Items	Project Information
			7	Document Submission List	Documentation
	Total Number of Reports Reviewed: 19			Total Number of Reports Reviewed: 27	
	Median Number of Pages per Report: 311			Median Number of Pages per Report: 250	

Further analysis of the sections requiring design progress information identified the specific data to be included in the reports. A summary of the required information extracted from various data sources is provided in Table 3. Project A used Oracle's ConjectPM (Oracle 2023) as their CDE for document submissions and approvals, and Project B used Bentley's ProjectWise. Despite the use of CDEs, design-related progress information was extracted from the CDE and manually recorded in Microsoft Excel submissions registers by a document controller. Subsequently, engineers extract the required information from these registers to prepare progress reports. The engineer determined Planned dates based on dates from a working program. While Project B presented the information in a table format, Project A presented such progress information in a plan layout format, depicted in Figure 3. These observations underscore the practical challenges in adopting new construction technologies, such as CDEs. Despite the availability of CDEs for data management in the projects, personnel still preferred using Microsoft Excel, a familiar tool, for tracking data. Additionally, it highlights methodological differences in data presentation between the projects, further illustrating the difficulties in standardizing progress reporting.



Dwg No	Schedule Sub	1st Sub	Schedule Reply	Actual Reply	Dwg No	Schedule Sub	1st Sub	Schedule Reply	Actual Reply	Dwg No	Schedule Sub	1st Sub	Schedule Reply	Actual Reply
1	04/06/16	23/05/16	14/06/16		8	30/05/16	27/05/16	17/06/16		15	14/07/16		04/08/16	
2	28/05/16	26/05/16	16/06/16		9	14/06/16		05/07/16		16	09/07/16		30/07/16	
3	21/05/16	26/05/16	16/06/16		10	29/06/16		20/07/16		17	27/05/16		17/06/16	
4	14/05/16	09/05/16	30/05/16		11	24/06/16		15/07/16		18	03/06/16	24/05/16	14/06/16	
5	07/05/16	06/05/16	27/05/16		12	19/06/16		10/07/16		19	10/06/16		01/07/16	
6	09/06/16		30/06/16		13	04/07/16		25/07/16		20	17/06/16		08/07/16	
7	04/06/16		25/06/16		14	16/07/16		06/08/16		21	24/06/16		15/07/16	

Figure 3. Weekly progress report of the drawing submission approval status plan at Project A (part-print)

Table 3. Progress-related information required for reports

Common Information Monitored	**Data Type**	**Project A Info. Source**	**Project B Info. Source**
Submission Number Ref.	String	ConjectPM / MS Excel Register	ProjectWise / MS Excel Register
Submission Description	String	ConjectPM / MS Excel Register	ProjectWise / MS Excel Register
Date of Submission	Date Time	ConjectPM / MS Excel Register	ProjectWise / MS Excel Register
Date of Response	Date Time	ConjectPM / MS Excel Register	ProjectWise / MS Excel Register
Status of Submission	String	ConjectPM / MS Excel Register	ProjectWise / MS Excel Register
Planned Submission and Planned Reply Dates	Date Time	Date determined by Engineer	Date determined by Engineer
Additional Information Monitored	**Data Type**	**Project A Info. Source**	**Project B Info. Source**
Location-Based Layout of Submission (Refer to Figure 3)	Image	ConjectPM / MS Excel Register	NA
Revision Number	String	NA	ProjectWise / MS Excel Register

3.2.3 Site progress reports

Referencing Table 2, both progress reports in Section 2 of Project A and Section 3.9 of Project B include updates on construction progress. Figures 4 and 5 illustrate how site progress is visually represented in these reports. Notably, Project A reports formwork and rebar activities separately from concrete casting, whereas Project B groups these tasks collectively under “RC works”. While Project B did not present rebar activity progress separately, the progress claim document necessitated this level of detail. Additionally, Project A details beam/slab and column progress on separate pages, in contrast to Project B’s consolidated presentation on a single page. Project A utilized visual demarcation to indicate progress, while Project B presented errors in visual demarcation and quantitative data. These differences further highlight the challenges of standardizing construction reporting due to the distinct characteristics of each project. Despite these challenges, the parametric nature of BIM supports diverse reporting formats as data is stored centrally and can be presented according to user requirements. Table 4 summarizes the required information and data types for both reports.

Table 4. Information requirement for reporting site progress

Information Monitored	Data Type
Area/Location Constructed	Image
Quantity Constructed To-date	Integer
Total Quantity to Construct	Integer
Percentage Completion	Integer
Planned Construction Date (Master Program)	Date Time
Target Construction Date (Working Program)	Date Time
Actual Construction Date by Area/Location	Date Time

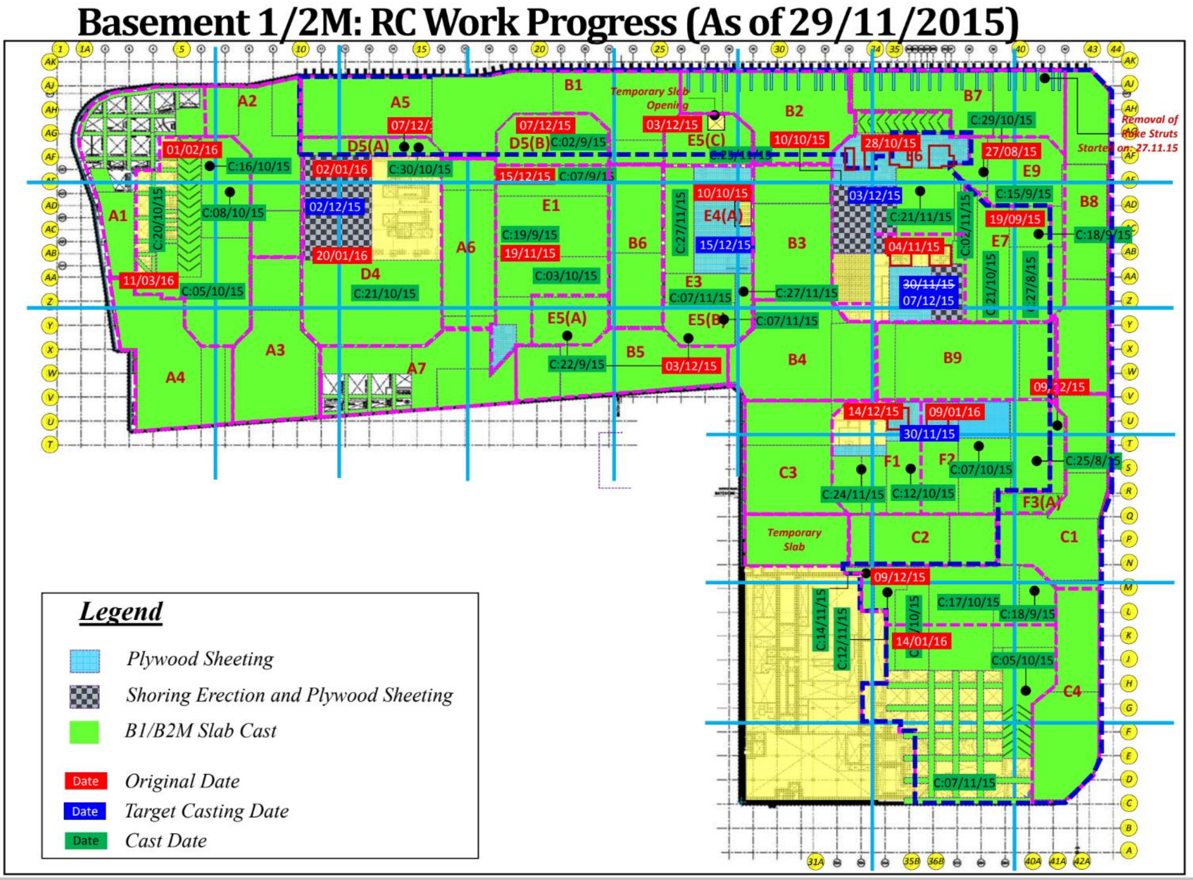


Figure 4. RC beam/slab progress report excerpt from project A in November 2015

Site Progress

Description	Unit	Quantity	Complete	Progress
Steel Pipe Pile	No.s	104	104	100 %
CBP 1500 mm	No.s	104	26	25.0 %
Bored Pile 1300 / 900 mm	No.s	96	0	0 %
Spun Pile 600 / 800 mm	No.s	5,955	5,021	84.3 %
Wharf RC Works	m^3	3,700	0	0 %
Staging Area RC Works	m^3	26,600	960	3.6 %
Drainage	m	230	110	47.8 %
M&E Trench	m	959	174	18.1 %
Marine Center Building	LS	1	0.25	25.0 %
Electrical Substation	LS	1	0.25	25.0 %
M & E	LS	1	0.14	14.0 %
Dredging	m^3	30,000	0	0 %
Wharf Facilities	LS	1	0	0 %
Road	m	290	0	0 %

Updated 24 Oct 2021

Figure 5. Site progress report excerpt from project B for October 2021

3.2.4 Progress claims and construction program

The analysis of progress claim documentation for both projects indicates that progress claims require more detailed input than the construction program, which does not necessitate such granular data. A detailed breakdown of the granularity required of the structural works is presented in Table 5 and Table 6. For example, while Project B's bored piling activity initially reported only total quantities completed, the progress claims needed these quantities broken down into stages like "casting complete" and "cutting of pile head." The latter refers to the process where piles are cut to designated levels, ensuring the concrete's quality at the structural base. These findings underline a significant challenge: current automated progress monitoring systems may not align perfectly with construction professionals' practical needs, as the specific requirements of different stakeholders like quantity surveyors and project managers are not adequately addressed (ElQasaby, Alqahtani and Alheyf 2022).

Table 5. Activity breakdown required for progress claims

Element	Units	Categorization	Progress Input Stages
Steel Pipe Pile Retaining Wall	Number	Pile Size	• Design • Delivery • Drive to Alignment • Drive to Level • Cutting of Pile Head
Bored Pile	Number	Pile Size	• Design • Casting • Cutting of Pile Head
Spun (Driven) Pile	Number	Pile Size	• Design • Delivery • Drive to Level • Cutting of Pile Head
Grout Pile	Number	Pile Size	• Design • Grouting
Reinforced Concrete Pilecap/Beam/Slab/Column	Number/m/m^2	Member Size	• Design • Reinforcing Bar • Formwork and Casting Concrete

Table 6. Activity breakdown required for construction schedule

Element	Units	Categorization	Progress Input Stages
Steel Pipe Pile Retaining Wall	Percentage	Location	• Design • Delivery • Installation
Bored Pile	Percentage	Location	• Design • Installation
Spun (Driven) Pile	Percentage	Location	• Design • Delivery • Installation
Grout Pile	Percentage	Location	• Grouting
Reinforced Concrete Pilecap/Beam/Slab/Column	Percentage	Location	• Design • Installation

3.3 Workflow-Based Project Monitoring System (WBPMS)

3.3.1 Overall framework

The WBPMS utilizes data generated during conventional construction processes to infer progress. As outlined in Figure 6, this system tracks the status of various documents - including design and shop drawings, delivery orders, and inspection records, as defined in the WorkflowDB. Acceptance of these documents by authorized personnel suggests that a construction substage has been completed, acting as an indicator of progress completion. These document statuses are then correlated with corresponding BIM elements, allowing for the calculation of progress completion percentages based on the quantities specified in the BIM properties.

Considering the potential of BIM as an integrating technology capable of hosting information from various databases, scripts were developed to automate the integration of available data into BIM, facilitating the generation of data required for input into progress reports, claims and schedules tailored to the needs of different stakeholders. The WBPMS utilizes a series of scripts to streamline progress reporting, which is elaborated in subsequent sections. An overview of the functions of each script is presented in Figure 7. Monitoring parameters are first created in BIM, and then elements are associated with the WorkflowDB and SystemsDB. Subsequently, the monitoring parameters are cross-referenced with the construction documentation database to assign a 'StageCode'. This code indicates the completion status and facilitates progress tracking through predefined workflows.

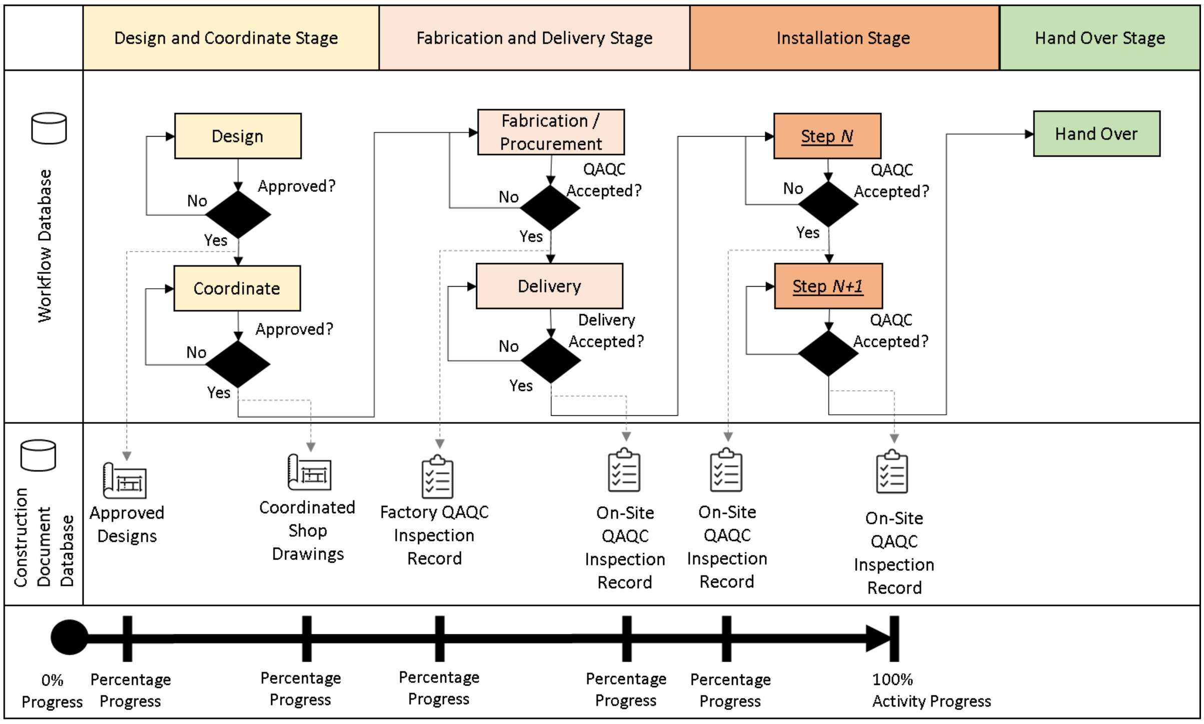


Figure 6. Conceptual overview of using document statuses to infer project progress

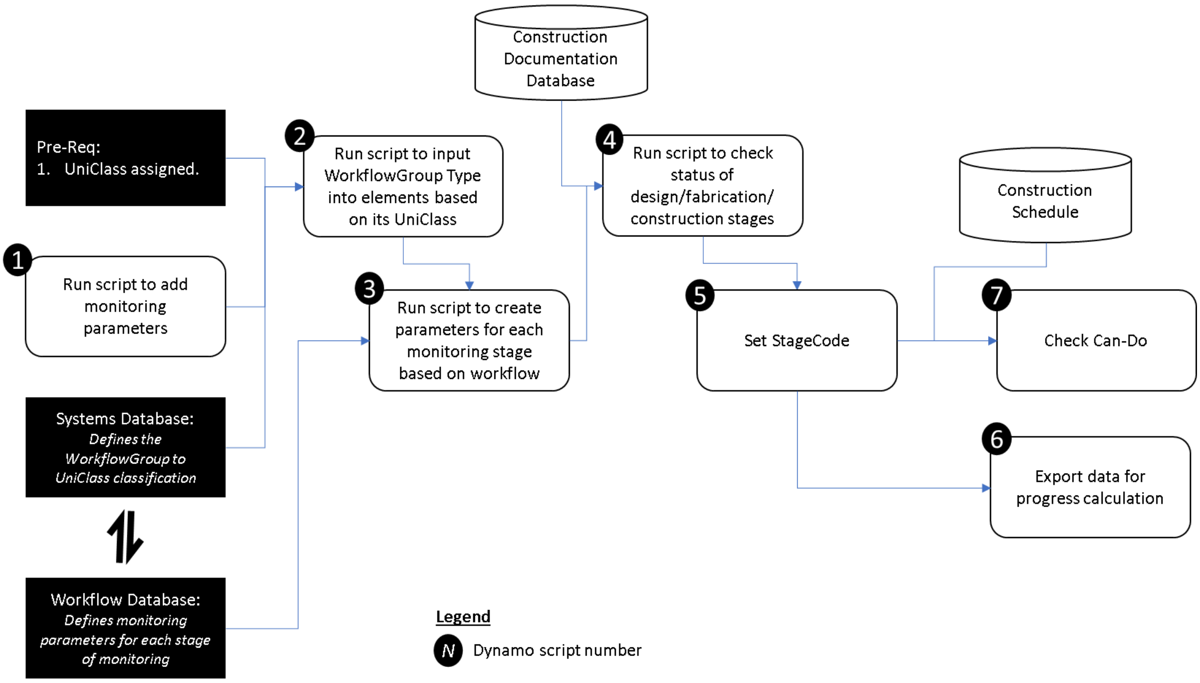


Figure 7. Overview of the WBPMS Process

3.3.2 Development of WorkflowDB and SystemsDB

A thematic analysis was utilized to pinpoint sections within reports that necessitate progress data reporting. Subsequently, a classification process was executed to categorize the required data types, such as text, images, dates, percentages, quantities, and other relevant variables, for each progress requirement identified. To further enhance the organizational structure, progress requirements were systematically grouped into coherent workflows, creating the WorkflowDB. For example, if progress monitoring for a concrete-in-place (CIS) reinforced concrete (RC) element required reporting to be separate for rebar installation and concrete casting, these stages of installation were classified as sub-stages of a CIS RC workflow as substage activity 1 and substage activity 2 respectively. Table 7 presents the information structure of the developed WorkflowDB that forms the basis for reporting progress. The use of a "SearchTerm" variable for searching through the construction documentation database facilitates flexible keyword searches across various databases.

The SystemsDB supports this structure by mapping UniClass Systems classification codes available from BIM elements to corresponding workflows. Each UniClass Systems classification at the object code level will be mapped to an identified workflow using expert knowledge. The data structure of the SystemsDB is presented in Table 8, which shows how the SystemsDB relates to the WorkflowDB. While the description column of the data structure is not essential for the WBPMS, it serves as descriptive data for easier user reference. In this manner, the WorkflowDB and SystemsDB data will be continuously populated to form a comprehensive monitoring database that can be used across all construction projects since workflows for constructing the same type of elements would not differ across construction projects. This methodology would eventually eliminate the need for manual extraction of data from registers and the manual consolidation of data to prepare progress reports.

The WBPMS first creates a set of data containers, termed Parameters, to prepare BIM for progress monitoring. These include "*WorkflowGroup*" and "*StageCode*." The *WorkflowGroup* parameter is associated as a type parameter and indicates the monitoring workflow that an element belongs to, and the *StageCode* parameter is associated as an instance parameter that identifies the current substage of an element.

Table 7. WorkflowDB structure with blue text indicating user-defined search terms

WorkflowGroup	<Workflow Name>
Design_Activity_Description	<Design_Doc_Parameter>
Design_Activity_Status	<Design_Status_Parameter>
Design_Activity_ResponseDate	<Design_ResDate_Parameter>
SearchTerm_Design	<Design_Doc_SearchTerm>
Fabrication_Activity_Description	<Fabrication_Doc_Parameter>
Fabrication_Activity_Status	<Fabrication_Status_Parameter>
SearchTerm_Fabrication	<Fabrication_Doc_SearchTerm>
SubStage_Activity1_Description	<Substage1_Doc_Parameter>
SubStage_Activity1_Status	<Substage1_Status_Parameter>
SearchTerm_1	<Substage1_Doc_SearchTerm>
SubStage_Activity2_Description	<Substage2_Doc_Parameter>
SubStage_Activity2_Status	<Substage2_Status_Parameter>
SearchTerm_2	<Substage2_Doc_SearchTerm>
SubStage_Activity3_Description	<Substage3_Doc_Parameter>
SubStage_Activity3_Status	<Substage3_Status_Parameter>
SearchTerm_3	<Substage3_Doc_SearchTerm>

Table 8. SystemsDB structure with user-defined <Workflow Name>

UniClass system classification code	**UniClass system classification description**	**WorkflowGroup**
<Object level UniClass system classification code>	<Object level UniClass System classification description>	<Workflow Name>

Existing BIM classification systems such as UniClass (NBS Enterprises Ltd n.d.), UniFormat (CSI® 2023), and OmniClass (CSI® 2023) categorize BIM elements for asset management but lack the granularity needed for reporting various construction stages. These systems may classify an element like a bored pile differently based on its function, yet the required progress monitoring stages remain the same, leading to redundancy in classification for the specific purposes of monitoring. For instance, a bored pile could be classified as "Ss_20_60_30_15: Contiguous pile retaining wall systems" or "Ss_20_05_65_41: In situ concrete bored piling systems" if it functions as a retaining wall or foundation system, respectively. However, the progress monitoring stages of the bored pile remain unchanged irrespective of its specific classification. To address this, the SystemsDB was developed to map

UniClass Ss Systems Classification with corresponding monitoring workflows. Validation of the SystemsDB and Workflow DB involved informal interviews with project managers. A script was then developed to assign the mapped workflow type to the *WorkflowGroup* Parameter in BIM.

Subsequently, a separate script was created to identify and establish monitoring parameters present in the workflow database for each BIM element, based on the assigned workflow data. This ensures that each element is monitored accurately according to its specific construction stages.

3.3.3 Relating BIM elements to document databases

The approach to using document statuses to infer construction progress was outlined earlier in Figure 6. This method involves querying the statuses of documents stored in various databases to determine the advancement of a construction activity.

The "search term" variable in the WorkflowDB facilitates keyword searches through the documentation database, allowing for the identification of document statuses. An "approved" status on a document signifies the completion of a stage within the workflow. Given that design, fabrication, and installation documentation are often stored in separate databases, the proposed approach is tailored to reflect this division.

Algorithm 1 details the process for linking BIM elements with their respective construction documentation across various project phases. Design documentation is typically established during the initial planning phase of a project, wherein each element is assigned to specific design packages, such as the piling design grouped under design package 1 and the other structures grouped under design package 2. This assignment is then recorded within the <Design_Doc_Parameter> of each element. A designated search term is then used to query the design documentation database, verifying its presence within the database. The latest status retrieved from this search is then updated in the <Design_Status_Parameter>.

For fabrication and installation phases, where documentation is generated post-fabrication or at construction start, the algorithm instead searches for the element's "mark" name and the corresponding search term from the WorkflowDB within the document description columns of the construction documentation databases. Upon finding a match, the algorithm updates the <Fabrication/Installation_Doc_Parameter> and <Fabrication/Installation_Status_Parameter> with the relevant data from the fabrication and installation databases.

Algorithm 1: Setting element status by searching construction documentation database

Input: *'BIM_element_instance'* , design document excel database, fabrication document excel database, installation document excel database, respective sheetnames, respective column headings for document description, document status, and submitted date

Output: Updated BIM with latest status based on Workflow stages

```
begin
    import data from WorkflowDB
    for each 'BIM_element_instance' , do
        get matching worfklow stages information from workflowDB
    end for
    import data from design document database
    for each 'DocumentDescription' in design document database, do
        create Dictionary of 'Status' with key: 'DocumentDescription'
        compare 'Date' to determine latest status
        update Dictionary values to contain only latest 'Status'
    end for
    for each 'BIM_element_instance' , do
        get 'Design_Document' data
        for each 'DocumentDescription' in the latest status Dictionary
            if 'DocumentDescription' is found in corresponding 'Design_Document'
            parameter of element
                set corresponding 'Status' to 'Design_Status' parameter
            end if
    end for
    import data from fabrication document database
    for each 'BIM_element_instance' , do
        get 'element_mark' data
        for each 'DocumentDescription' in fabrication document database, do
            if 'SearchTerm' and 'element_mark' are in 'DocumentDescription'
                get corresponding 'Fabrication_Doc _Reference' and 'Fabrication_Doc_Status'
                get corresponding 'Fabrication_Doc _Parameter' and
                'Fabrication_Status_Parameter'
                if 'element_mark' match:
                    set 'Fabrication_Doc_Reference' into 'Fabrication_Doc_Parameter'
                    set 'Fabrication_Doc_Status' into 'Fabrication_Status_Parameter'
                end if
            end if
        end for
    import data from installation document database
    for each 'BIM_element_instance' , do
        get 'element_mark' data
        for each 'DocumentDescription' in installation document database, do
            if 'SearchTerm' and 'element_mark' are in 'DocumentDescription'
                get corresponding 'Installation_Doc_Reference' and 'Installation_Doc_Status'
                get corresponding 'Installation_Doc_Parameter' and
                'Installation_Status_Parameter'
                if 'element_mark' match:
                    set 'Installation_Doc_Reference' into 'Installation_Doc_Parameter'
                    set 'Installation_Doc_Status' into 'Installation_Status_Parameter'
                end if
            end if
        end for
    end for
end
```

Subsequently, another script evaluates the updated status of elements by applying if-then rules to determine completion along the workflow. If the design stage is “approved”, “Code 1” is assigned to the ‘StageCode’ parameter; if the fabrication is complete, “Code 2” is designated. For installation, the script checks the sub-stages – starting with 3c, and going backwards to 3a since not all activities have three sub-stages. If specific criteria as defined in the WorkflowDB are met, the appropriate stage codes (3c, 3b, 3a) are assigned accordingly.

Lastly, to track progress by scheduled activity in the construction programme, the WBPMS utilizes the Activity ID from the element’s metadata, grouping elements by count, area or volume under respective Activity IDs. Elements are then categorized by their StageCode to reflect different construction phases (design, fabrication, installation), with total quantities calculated per category. Progress percentages are determined by comparing the quantity of elements at a specific stage to the total quantity under each Activity ID, providing a clear metric of progress at each construction phase.

3.3.4 Evaluation metrics

Upon developing the WBPMS, it will be applied to an actual project to demonstrate its feasibility based on the following checklist:

(1) Can it successfully replicate the data and data formats in progress reports?
(2) Can it replicate and present data in progress reports more quickly than the conventional process?
(3) Does the replicated data align with the data presented in the actual progress reports and progress claims?

These questions will evaluate the effectiveness and accuracy of the results produced by the WBPMS.

3.4 Application of framework to a piling activity

3.4.1 Establishing SystemsDB and WorkflowDB

The WBPMS was utilized for piling activities in Project B to validate the proposed methodology. The piling model, developed in Autodesk Revit, incorporated UniClass classifications as stipulated by the contract. This model included a seawall made of contiguous bored piles encased with interlocking steel pipe piles and grout piles for watertight integrity as shown in the blow-up details in Figure 8. Installation of the seawall proceeded with the steel pipe piles, followed by bored piles, and grout piles last. The staging ground closer to the seawall was supported by bored pile foundations, and the rest of the structure was supported by driven piles, as shown in. Due to delays in relevant ground investigation work caused by COVID-19, the design of the piles had to be split into the regions demarcated in Figure 8, indicated by their design submission numbers “ST *n*,” which will be used for design stage monitoring.

Based on the information requirements from various construction documents, WorkflowDB and SystemsDB were developed for Project B, as outlined in Table 9 and Table 10, respectively. Referring to the information requirements for progress reports, progress claims and the construction schedule shown in Figure 5, Table 5 and Table 6 respectively, the progress claim requires the most granular level of monitoring stages. For instance, for the spun pile installation progress, the progress report only required quantities of installed piles to be presented, whereas the progress claims required the quantities of piles that have been cut to the design level to be reported. The part of the pile that is required to be cut is indicated in Figure 9. Hence, a workflow group for “DrivenPiling” is defined with the following monitoring stages of design, fabricate, installation substage 1 – pile installation and installation substage 2 – pile cutting. On the other hand, the identified workflow group for “BoredPiling” has a similar 2-substage installation monitoring criteria, but its workflow group was created because none of the progress documents required monitoring of the delivery stage of the bored pile activity in this project. Similarly, other workflow groups were created, populating the WorkflowDB. Upon identifying the unique workflow groups required for the monitoring, the workflow groups are then mapped to the UniClass System classification by expert knowledge of the installation methodology of various piling systems, forming the SystemsDB.

Since the SystemsDB relies on the UniClass System Classification for mapping BIM elements to monitoring workflows, the BIM classification used has to be of sufficient granularity. If the UniClass System input for the project utilized only a Section Level input, that is, classifying all piles as “Piling System” regardless of pile types, there would be insufficient information to know whether the pile to be monitored should be a bored pile or a driven pile for instance. Hence, a Section Level UniClass System Classification system input was included in the SystemsDB to inform users of such cases.

These databases facilitate monitoring across different stages including design, delivery, pile driving alignment, installation, and cutting activities. Utilizing the UniClass System classification, the workflows categorized five systems into four distinct monitoring workflows, each specifying requisite stages within the WorkflowDB. Notably, delivery was reported only for prefabricated elements to support a payment scheme under contractual terms that allowed the contractor to be paid for materials delivered to the site (Building Construction Authority of Singapore 2020). Each workflow’s monitoring stages are comprehensively detailed in the WorkflowDB and aligned with the UniClass Systems specified in the SystemsDB.

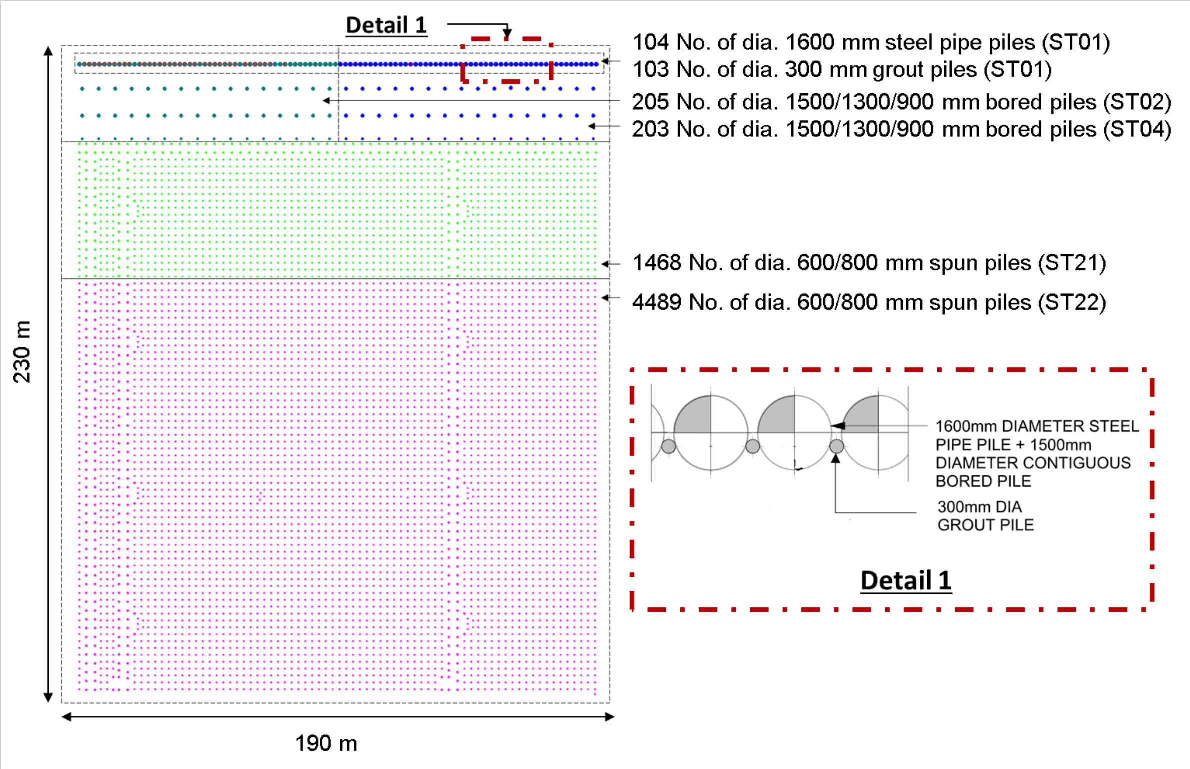


Figure 8. Plan layout of various pile types, demarcated by design groups

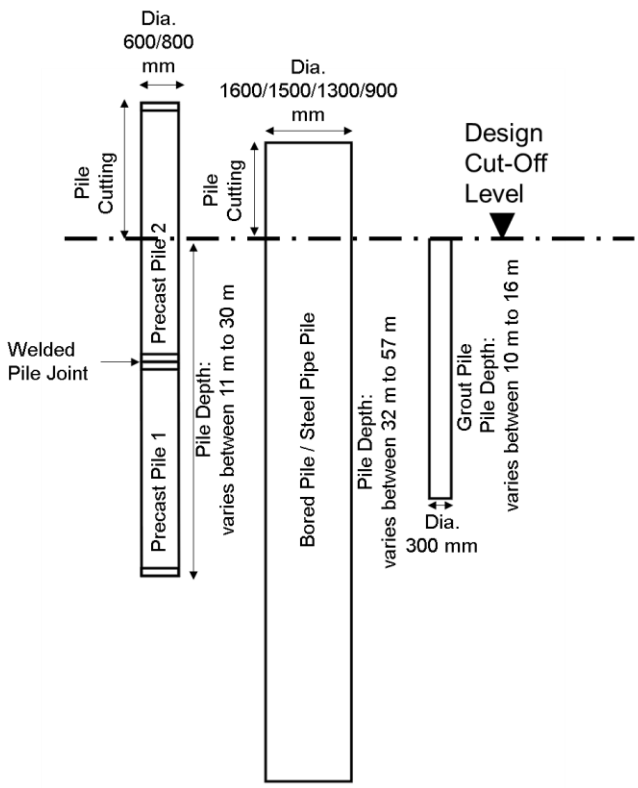


Figure 9. Typical cross-section of various pile types

Table 9. WorkflowDB for piling activity for Project B

WorkflowGroup	BoredPiling	DrivenPiling	RetainingWallPiling	GroutPiling	Corresponding StageCode
Design_Act_ Description	Design_Doc	Design_Doc	Design_Doc	Design_Doc	
Design_Act_ Status	Design_Status	Design_Status	Design_Status	Design_Status	1
SearchTerm Description	*ST*	*ST*	*ST*	*ST*	
Fab_Act_ Description	Fabrication_Doc	Fabrication_Doc	Fabrication_Doc	Fabrication_Doc	
Fab_Act_Status	Fabrication_Status	Fabrication_Status	Fabrication_Status	Fabrication_Status	2
SearchTerm Fabrication	-	*delivery*	*delivery*	-	
SubStage_Act1_Description	-	-	*PileAlignment_ Doc*	-	
SubStage_Act1_Status	-	-	*PileAlignment_ Status*	-	3a
SearchTerm1	-	-	*initial stage*	-	
SubStage_Act2_Description	*PileInstallation_ Doc*	*PileInstallation_ Doc*	*PileInstallation_ Doc*	-	
SubStage_Act2_Status	*PileInstallation_ Status*	*PileInstallation_ Status*	*PileInstallation_ Status*	-	3b
SearchTerm2	*installation*	*installation*	*final stage*	-	
SubStage_Act3_Description	*PileCutting_Doc*	*PileCutting_Doc*	*PileCutting_Doc*	*PileGrouting_Doc*	
SubStage_Act3_Status	*PileCutting_Status*	*PileCutting_Status*	*PileCutting_Status*	*PileGrouting_ Status*	3c
SearchTerm3	*cutting*	*cutting*	*final stage*	*grout piling*	

Table 10. SystemsDB for piling activity

Code	Title	Assigned WorkflowGroup
Ss_20_05_65	Piling Systems	Error - Insufficient Information
Ss_20_05_65_24	Driven Precast or Prestressed Concrete Piling Systems	DrivenPiling
Ss_20_05_65_41	In situ Concrete Bored Piling Systems	BoredPiling
Ss_20_60_30_13	Combi Retaining Wall Systems	DrivenPiling
Ss_20_05_80_71	Retaining Wall Cementitious Grout Systems	GroutPiling
Ss_20_60_30_15	Contiguous Pile-Retaining Wall Systems	BoredPiling

3.4.2 Preparing the model for linking to document databases

After establishing the WorkflowDB and SystemsDB, Dynamo scripts were run via the Dynamo Player to perform the initial stages of the WBPMS. These stages included linking elements to workflow groups and enhancing the model with parameters essential for integration with document databases. The results, presented in Figure 10, showed successful workflow assignments to element types and the creation of monitoring parameters associated with the respective Revit categories. Subsequently, planning data indicated by the design demarcations in Figure 8 was manually entered into the "Design_Doc" parameter for each element. This initial setup ensures that each element is properly categorized and linked for ongoing monitoring.

3.4.3 Element statuses based on document statuses

3.4.3.1 Design database and statuses

For this study, two versions of design submission registers were used: one maintained in Microsoft Excel, and another exported from the ProjectWise database (Bentley 2023). These registers tracked design submissions to authorities and clients. The keywords employed during the preparation of construction documentation served as the search terms for each monitoring stage. The search term for the design stage for Project B is denoted by "ST" and input into the WorkflowDB illustrated in Table 9.

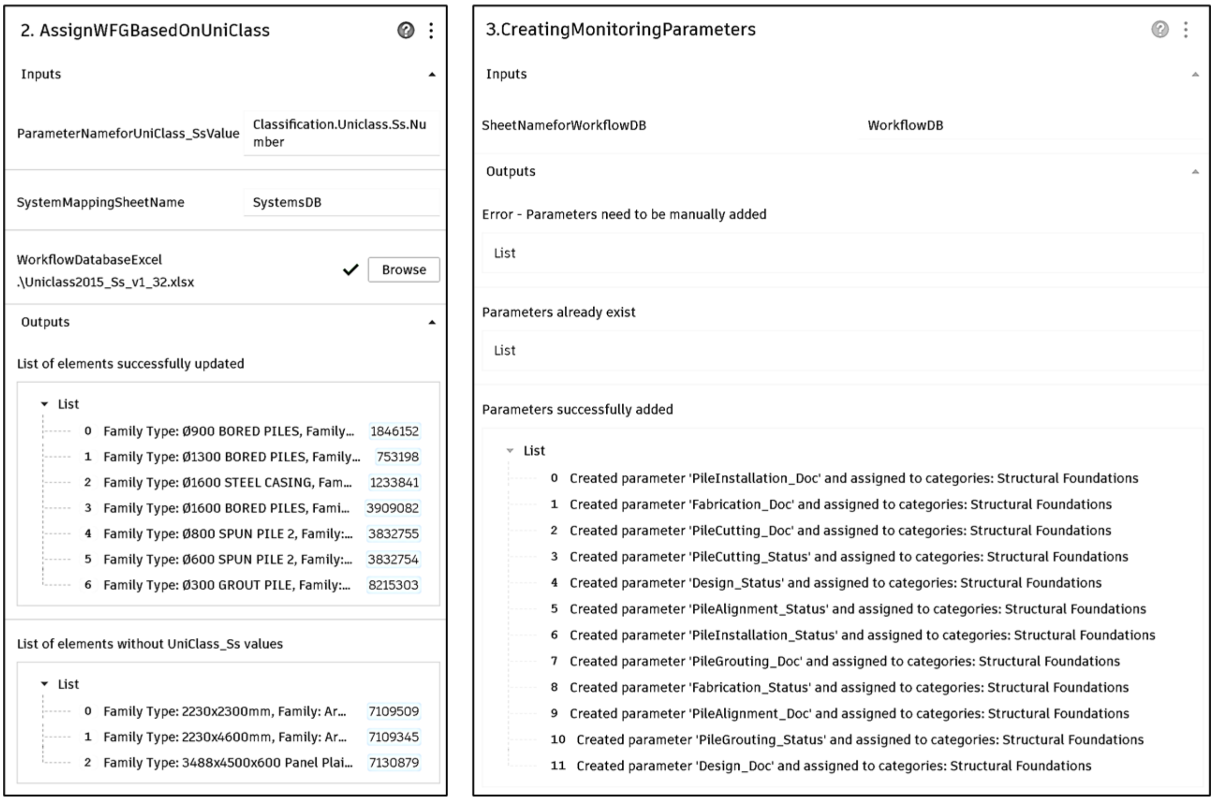


Figure 10. Dynamo Player results for script two (left) and script three (right) of the WBPMS

The fourth step of the WBPMS involves configuring the database search parameters, specifying the column names for document descriptions, statuses, and relevant dates, as demonstrated in Figure 11. Due to the structural differences between Excel and ProjectWise, the Excel data required reformatting to ensure compatibility and effective integration. This included aligning data structures and unmerging merged cells for the script to be able to read each row of data effectively. While Microsoft Excel shares similarities with databases in terms of data storage and management, it lacks the structured query capabilities and relational integrity constraints inherent to database systems, rendering it unsuitable for database-like searches when data are not organized in a structured manner. Nonetheless, the project team had to maintain a separate design submission register for tracking submissions to authorities who did not have access to the project’s ProjectWise environment. As a result, there were two sets of documents that had to be merged into a single database. Lastly, to simulate the timing of milestones for the submission of progress claims, progress reports, and progress schedules, the data were partitioned into separate Excel sheets, where each sheet represents the extent of data completion up to a specific cut-off date.

Once the necessary inputs are updated, the same set of information is identified for the corresponding delivery and inspection databases.

3.4.3.2. Delivery and inspection database

For the study on pile delivery activities, several documents were utilized, including a spun pile delivery and installation register in Microsoft Excel, and Version 1 and Version 2 Hubble Inspection Registers exported from the Hubble Quality Management System database (Hubble 2023). The search term corresponding to each workflow's sub-construction activity monitoring is presented in Table 9, and input into the Dynamo script is shown in Figure 11.

Similarly, these documents required significant data cleaning due to inconsistencies in the "Mark" values used as identifiers. For instance, while some entries in the inspection descriptions were meticulously input as "BP-35, BP-36, BP-37," others were entered as "BP-35 to BP-37," potentially leading to missed updates for BP-36's status. Moreover, the engineers opted not to use the Hubble system for spun pile inspections as they had the perception that such systems would result in them having an additional workload. Instead, yet another set of registers specific to spun pile installations was maintained. Inspections for spun piles required attaching a hardcopy pile set measurement record to the inspection records, which posed difficulties in document management when such records contained a mix of digital and hardcopy. The pile set measurement record consists of a grid paper affixed to a pile, with a worker using a pencil to measure the penetration of the pile into the ground per hammer blow. Utilizing the Hubble system for spun pile inspections would require engineers to perform additional tasks: returning to the office to scan hardcopy measurement records and attaching them to the digital inspection forms. This would significantly increase the workload due to the need for manual handling and digital integration of these documents. Consequently, this set of spun pile installation inspection data had to be formatted and merged into the Version 2 Hubble Inspection Register database format. Similarly, Version 1 data were integrated into the Version 2 format due to its use preceding the migration to a newer version of the system. Similar to the design database, the data were organized into separate Excel sheets categorized by specific cut-off dates for simulation. In Project B, there was no separate database for delivery inspections and installation inspections. Users were required to input the column heading name containing the description of the inspection, the reference number of the inspection, and the date on which the inspection was approved.

In the exported data from the Hubble inspection database, the date of inspection approval was not recorded. However, it was observed that the approval date was captured in one of the digital form options signed off by authorized personnel. Therefore, without an explicit approval date, the inspection deadline was employed as a substitute for the approved inspection date.

The WBPMS could not track the delivery of specific spun piles due to their non-unique characteristics. These prefabricated piles, standardized at lengths of 6 m, 9 m, and 12 m and diameters of either 600 mm or 800 mm, could be used interchangeably across various locations. Instead, the project team used a method that involved comparing the total length of piles delivered with the total design pile length to gauge delivery progress. This method provided a practical solution for monitoring the overall deployment of materials without tracking individual pile locations.

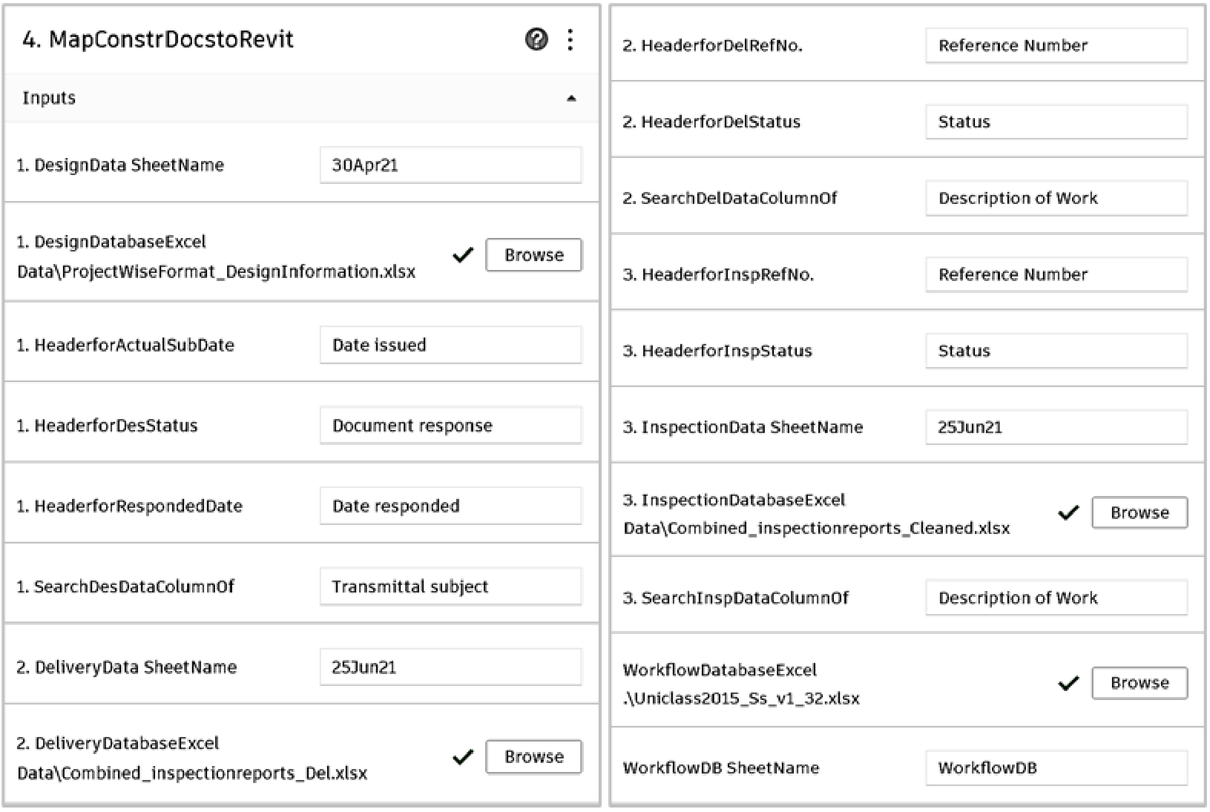


Figure 11. Input variables for the fourth step of the WBPMS

3.4.4 Setting StageCode and obtaining progress against construction schedule activities

After updating the relevant information from the database into elements, the fifth step of the WBPMS involves evaluating the status of each element's monitoring stage to determine the appropriate StageCode. Users need to establish the acceptance criteria, as illustrated in Figure 12. For instance, an "Approved" status in a design document indicates the completion of that stage, allowing progression to subsequent stages like fabrication or construction.

Additionally, to ensure that progress updates correspond with the construction schedule, the WBPMS uses the Activity ID specified during the 4D model preparation. This ID helps to group elements and calculate progress percentages accurately, aligning updates with the planned construction activities.

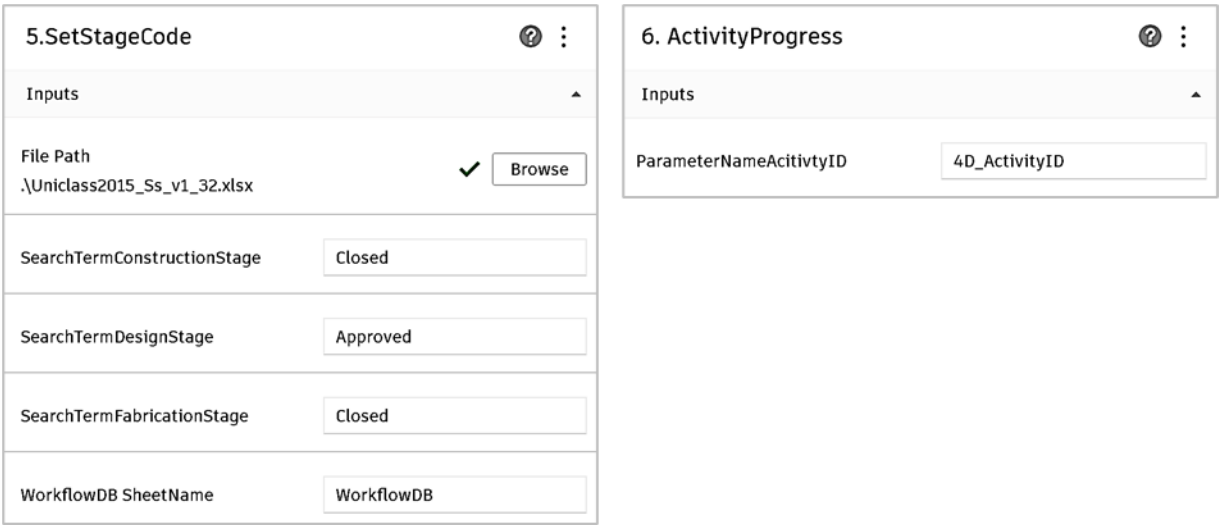


Figure 12. Input variables for the fifth step (left) and sixth step (right) of the WBPMS

3.5 Results

3.5.1 WBPMS output

Although Project B did not require layout-based design status reporting, the WBPMS demonstrated its capability to automatically generate such reports from BIM. This was facilitated by linking BIM elements with a design database, allowing for direct information extraction into the model, as demonstrated in Figure 13. In this setup, Revit Tags are used to annotate each element with its status and response date, updating dynamically with each data refresh. This automation not only saves substantial time in report preparation but also allows for customizable data filters. These filters can colour-code elements based on their statuses, improving the visualisation and usability of the generated reports.

Figure 14 displays the output of the WBPMS for construction progress reporting, showing information similar to that required in Figure 5. This output can be enhanced visually for presentations by overlaying site background images as needed. Furthermore, the quantities categorized by StageCode are utilized for reporting in progress claim documents, ensuring that the reported quantities align precisely with the documented progress, thereby streamlining progress data extraction to be used with various documents.

Lastly, Figure 15 depicts the WBPMS output for two specific activity IDs, showing how the system utilizes StageCode values to help planners assess the progress of various construction activities, particularly focusing on design and fabrication stages not typically included in 4D BIM inputs. The progress percentage completion by stage code, and then by element count, area and volume are presented as nested lists for each unique activity ID. For instance, in the case of spun pile installation with activity ID 7.1.4.2 (right image), the sum of the percentage completion of the count of elements with StageCode 1 of 77.6% and StageCode 3a of 22.4% suggests that there is a 100% completion of the design phase since the elements cannot be constructed without completion of its design. Although 22.4% of the spun pile installation's first monitoring stage is complete, indicated by the percentage progress of elements with StageCode 3a, this suggests that the final pile-cutting installation sub-activity has not been completed. Therefore, planners can use this detailed breakdown to adjust progress inputs into the schedule more accurately or to redefine what constitutes the completion of an activity. This detailed reporting aids in precise schedule updates and improves project management oversight.

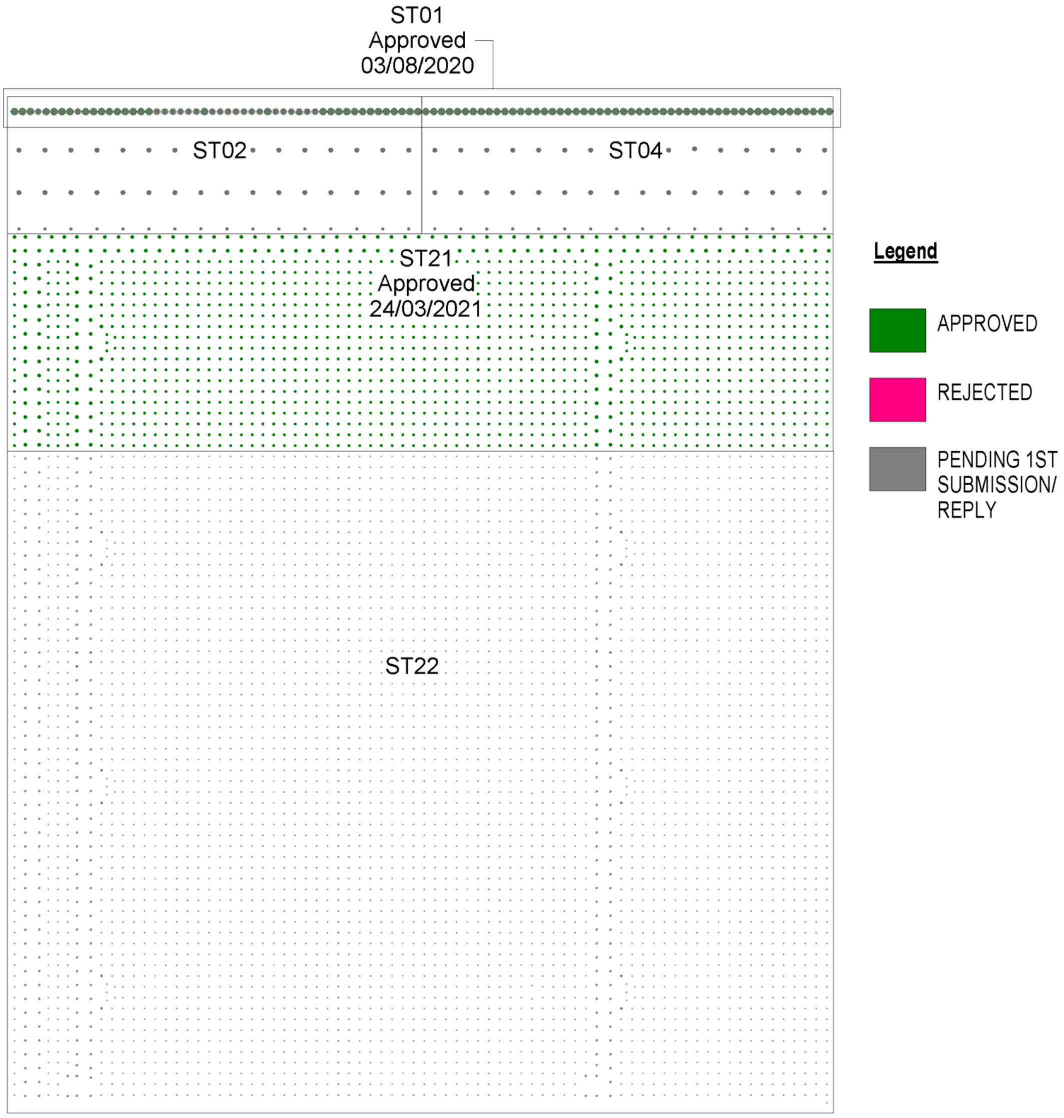
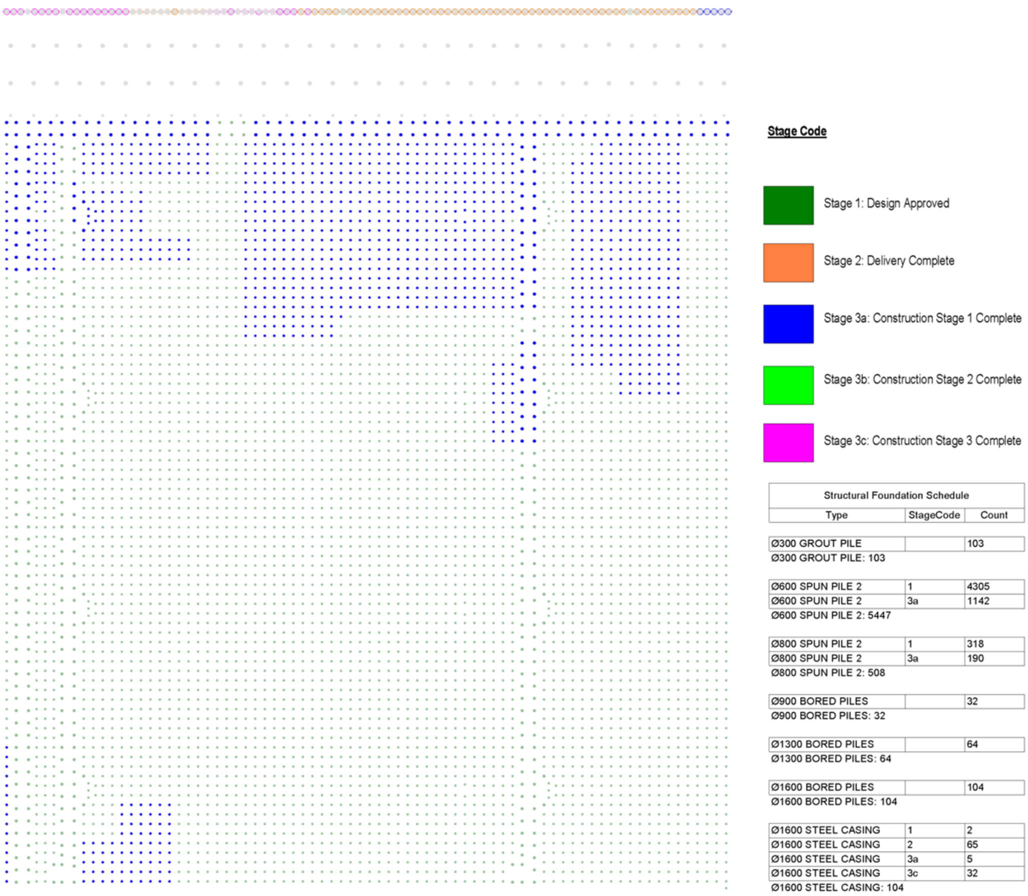


Figure 13. Layout-based design progress report from WBPMS as of 28th March 2021



Structural Foundation Schedule		
Type	StageCode	Count
Ø300 GROUT PILE		103
Ø300 GROUT PILE: 103		
Ø600 SPUN PILE 2	1	4305
Ø600 SPUN PILE 2	3a	1142
Ø600 SPUN PILE 2: 5447		
Ø800 SPUN PILE 2	1	318
Ø800 SPUN PILE 2	3a	190
Ø800 SPUN PILE 2: 508		
Ø900 BORED PILES		32
Ø900 BORED PILES: 32		
Ø1300 BORED PILES		64
Ø1300 BORED PILES: 64		
Ø1600 BORED PILES		104
Ø1600 BORED PILES: 104		
Ø1600 STEEL CASING	1	2
Ø1600 STEEL CASING	2	65
Ø1600 STEEL CASING	3a	5
Ø1600 STEEL CASING	3c	32
Ø1600 STEEL CASING: 104		

Figure 14. Layout-based construction progress report as of 31st May 2021

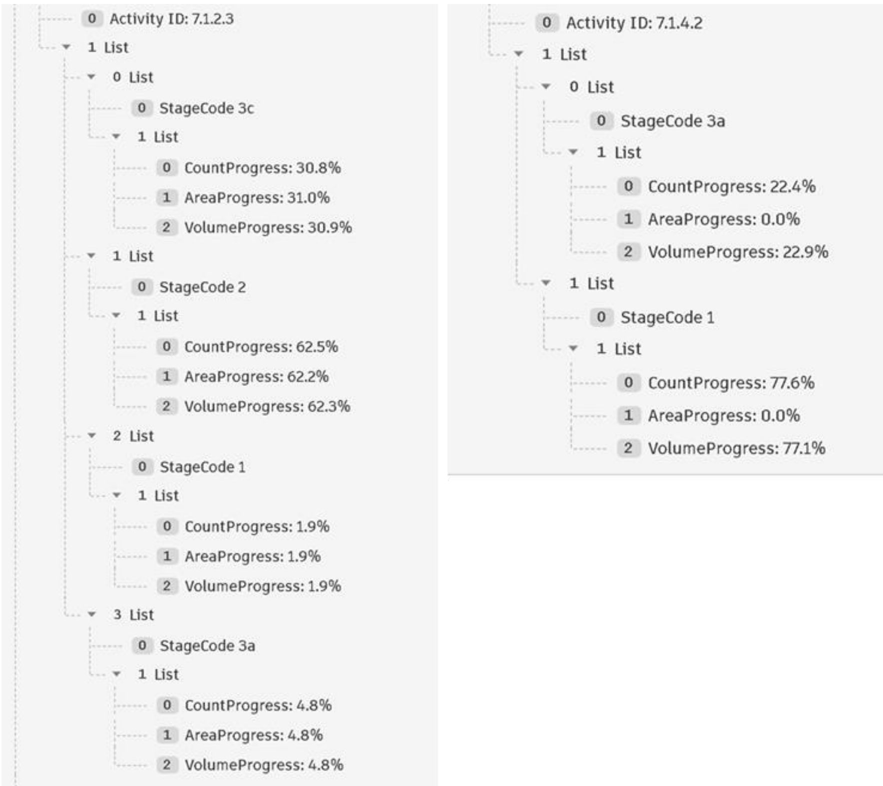


Figure 15. Activity-ID-based progress output for two activity IDs

3.5.2 Evaluation of results

3.5.2.1 Design progress reports

A side-by-side comparison of the WBPMS output and the required data to be presented in conventional reports is presented in Figure 16, showing that the key information required to be presented was successfully replicated by the WBPMS.

While specific data on the amount of time required to prepare the design progress reports was unavailable, the steps involved in preparing the conventional report include (1) checking the design submission Excel register for each document's approval status, (2) if the submission was responded, to change the colour of the geometry representing the design zone as per the legend, (3) then input the date responded on the layout and in the table, (4) and lastly, repeat steps 1 to 3 for each level and design submission type each week. In comparison, the WBPMS requires a user to run Steps 1 to 3 once per model, and then Steps 4 and 5 as and when reports are required to be created, suggesting a higher efficiency as compared to the conventional method.

Since the piling project did not submit a layout-based progress report, and submitted only the table of submission and replies, a direct comparison cannot be made. Nonetheless, all results aligned since the data that the WBPMS was reading came from the design submission register, and screenshots of the design submission register were used in the progress report.

A direct comparison of design progress against progress claims cannot be made as design progress was broken down by a fixed monthly component with milestone payments rather than a document-based approach.

3.5.2.2 As-installed progress reports and progress claims

Similarly, the comparison for the site progress report is presented in Figure 17, showing that the key information required to be presented was successfully replicated by the WBPMS, except for percentage-type data. Percentage-type data could not be directly reproduced in Revit due to software limitations, which lack spreadsheet-style functionality for data presentation.

While specific data on the amount of time required to prepare the site progress reports were not formally investigated, informal interviews with the engineer preparing the report revealed that it takes up to half a day to prepare the weekly site progress reports. The steps involved include (1) checking the database of installed piles sorted by the last week that it was installed, (2) highlighting the piles that were installed on a hardcopy design plan by matching the pile mark, (3) transferring the data into PowerPoint slides using the shapes function to overlay approximate location of installed piles over the actual site photo, (4) lastly, steps 1 to 3 are repeated for each pile type, and quantities are extracted using formulas in the Excel register. In comparison, similar to design progress updates, only Steps 4 and 5 of the WBPMS need to be run as and when the progress reports are required to be produced.

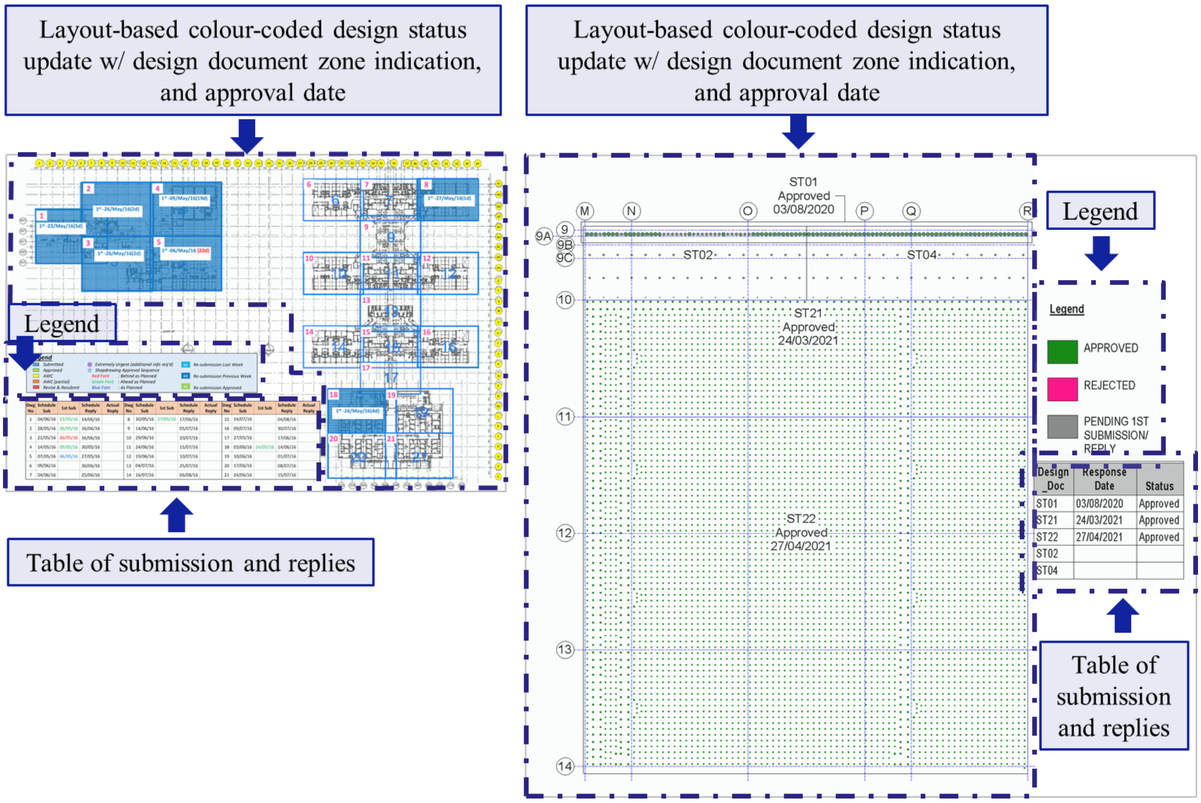


Figure 16. Comparison of conventional design progress (left) and WBPMS output (right)

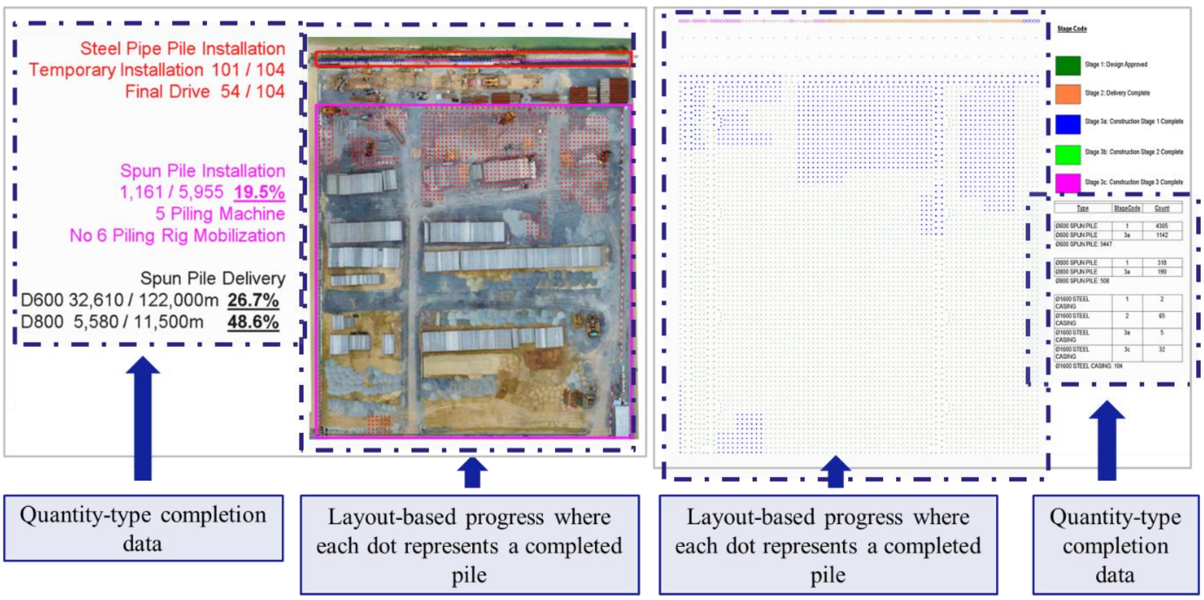


Figure 17. Comparison of conventional site progress (left) and WBPMS output (right)

Table 11 presents the quantity comparison of reported progress across the progress report, progress claim and WBPMS output for May. It is worth noting that the progress claims were dated 31st May 21 and the progress reports 27th May 21, suggesting that the progress information had to be retrieved twice by different stakeholders, and hence reported progress quantities would also slightly differ. While the number of spun piles reported to be installed aligned largely with the progress claim report, the slight difference in reported quantity could be attributed to delayed data entry since installation registers were manually updated from spun pile installation records, highlighting the latency of information transfer due to manual methods.

Table 11. Comparison of progress quantity between WBPMS and actual project documentation

Document Reports Dated	**Progress Report 27/05/24**	**Progress Claim 31/05/24**	**WBPMS 31/05/24**
ø1600 mm steel pipe pile delivered	Not reported	105	102
ø1600 mm steel pipe pile 1st stage installation	101	89	5
ø1600 mm steel pipe pile 2nd stage installation	54	67	32
ø600 mm spun pile installation	Not reported	1139	1142
ø800 mm spun pile installation	Not reported	190	190
Sum of spun pile installation	1161	1329	1332

However, quantities for the steel pipe pile installation varied widely across both documents, as well as the WBPMS. Despite the progress claim being dated later than the progress report, fewer quantities were reported to be installed for the first installation stage, namely the pile to alignment stage. The discrepancy was due to the requirement of attaching a signed copy of a drawing by an authorized inspector, which had to be prepared in advance before the submission of the claim, whereas, the weekly progress report was updated based on the latest information received from the site, and did not require such verified document for substantiation. However, when comparing the quantities for the second installation stage, the progress report reported fewer quantities than the progress claims. The project team was unable to give a reason as to why there was such a discrepancy, since the progress claim quantities were endorsed by an authorized inspector.

On the other hand, the WBPMS reported the least quantity due to the data field limitations of the digital inspection system that was used. Only the following dates were available from the Hubble Digital Inspection System database to be extracted, namely 'inspection request created date' and 'inspection deadline'. Since requests are typically created before actual inspection dates for the inspector to plan his schedule, using this date as the criteria to infer progress was not suitable. 'Inspection deadline' refers to the time when the inspection shall be completed, suggesting that the element would have already been inspected by that date, which would have been a later date than the actual inspected date. Thus, this data field was used as the date completion criteria to check the status of the inspection for inferring progress. The ideal date to be used would have been the actual date that was approved by the inspector, which was not available in the database for retrieval but was printed in individual inspection reports.

Hence, the discrepancy in the WBPMS quantities compared to the reported quantities arose because the engineers who created the inspection record had overestimated the deadline for the inspection completion of the pile. Instead, these piles were reported to be completed by the 27th of June in the WBPMS. The total number of steel pipe piles delivered also does not align with the progress claim data.

Investigation of the inspection records revealed that piles with marks SPP-049 and SPP-090 were not captured due to typo errors in the inspection description. However, further investigations into the delivery order documents revealed that the materials for these 2 piles were indeed delivered, but not attached to any of the inspection records, suggesting that these piles might have been missed out during material inspection processes and were not inspected. While the progress report in Figure 17 indicated a total of 104 steel pipe piles are to be installed, the progress claim indicated that 105 piles were delivered. This was due to certain design changes that occurred due to site conditions, but the information was not passed on to the quantity surveyor team for documentation updates.

In summary, while it was demonstrated that the WBPMS can efficiently replicate progress reporting requirements, and potentially improve data latency issues due to the retrieval of live data from construction databases, the accuracy of the reports still largely relies on accurate data that is stored within the databases, warranting further research into how inspection data can be more accurate.

3.6 Discussion

While the WBPMS has proven effective in integrating BIM elements with construction documentation databases to streamline progress reporting, it does have its limitations. This section will explore these limitations and discuss the significance of the findings. The main constraint lies in the system's dependency on the accuracy and timeliness of input data; any delays or errors in data entry can lead to inaccurate progress tracking. Additionally, the reliance on specific software platforms may limit flexibility and adaptability. Understanding these limitations is crucial for optimizing the use of BIM in construction projects.

3.6.1 Availability of structured data

This study highlighted the continued prevalence of Microsoft Excel in the industry despite the adoption of CDEs, attributed to both organizational inertia and user familiarity with traditional tools. The effectiveness of the WBPMS hinges on having access to well-structured construction documentation databases and standardized data input practices. The system's dependence on specific search terms for navigating these databases highlights the critical need for uniform data management practices. However, the prevalent use of Microsoft Excel, characterized by its flexibility and lack of standardized data structuring, poses significant challenges for the WBPMS.

While adopting a CDE or digital management system, such as the Hubble Quality Management System, can significantly improve the accessibility of structured data, their effectiveness is limited by the database architecture of these systems. A significant issue identified was the inability to export the inspection approval date from Hubble, pointing to a potential shortfall in the system's data structuring. This limitation illustrates a broader challenge that current technological solutions may not fully meet the operational needs of construction professionals (Hasan and Sacks 2023), as the necessary data is stored but not readily accessible due to structural limitations in the database. This gap highlights the need for systems that align better with practical industry requirements and the need to further investigate and standardize the minimal requirement of the data accessibility of digital management systems.

3.6.2 Manual data entry in CDEs

While CDEs may address the specific limitation of the availability of structured data, it does not mitigate the issue of potential human errors during data entry they do not mitigate the issue of potential human errors during data entry, such as those that may occur during the creation of digital inspections. This was evident in the issues encountered in the previous section. During the data cleaning process of the exported databases, common typo errors were observed, such as "installation" being entered as "instellation" or pile marks being entered with the letter 'O' replacing the numeric value of '0' resulting in inputs such as "SP-O1" instead of "SP-01". Cases where elements were missed out were also encountered. Since the WBPMS uses keyword searches for information retrieval, these errors, although menial, will pose challenges to the WBPMS for updating progress statuses.

While there is a possibility to kickstart workflows by pre-creating data on the CDE in a controlled environment, which may reduce such errors, the possibility would depend on the available functionality of the CDE. In this study, where ProjectWise was used for the design stage submissions and the Hubble Inspection system for the fabrication and installation stage inspections, both software did not possess such functionalities. Once an entry was created in the CDE, the entry would be assigned an 'open' status, indicating that the next stakeholder is required to take action in the process. However, alternative CDEs such as the Submittal function of Autodesk Build (Autodesk 2024), allows entries to be in a 'draft' state, which allows users to pre-create entries that will correspond with progress monitoring requirements, thus streamlining the progress monitoring process. However, this improved process fundamentally reverses the conventional approval workflows presented Figure 6, where approvals are created only when documents/materials/sites are ready for approval. While the process may theoretically streamline progress monitoring, further studies will be required to investigate the feasibility and acceptability of these methods in practical settings. On the other hand, there is a possibility to improve inspection processes by automating the inspection function such that manual human intervention can be reduced. The theoretical possibilities of automating inspections are discussed in Chapter 4, and its feasibility is presented in Chapter 5.

Additionally, to overcome the keyword-search limitation of the proposed WBPMS, integrating advanced technologies, such as large language models (LLMs) could be transformative. LLMs can enhance the keyword search functionalities due to their enhanced reasoning abilities (Zhu, et al. 2023), offering a more intuitive and flexible approach that will address current keyword search limitations such as typo errors or varied terminology that could hinder data retrieval. Nonetheless, it is important to recognize limitations in LLM application, such as hallucinations. For example, in the case where a certain element's inspection was missed, LLMs may falsely project that those elements should have been included and reflect such results accordingly. Thus, employing rigorous validation processes and incorporating checks within the system to ensure data accuracy and reliability would be required should LLMs be incorporated.

3.6.3 Monitoring of non-unique elements

Another challenge identified in this study involves the tracking of non-unique elements, such as prefabricated piles with standardized dimensions. Due to their interchangeable nature and absence of unique identifiers, monitoring of the fabrication stage by location for these elements posed significant challenges for the WBPMS. The system is designed to link specific elements to unique workflow stages and associated documentation, but it struggles to track these standardized components effectively. This limitation underscores the need for enhanced tracking mechanisms that can accommodate the generic nature of certain construction materials.

This challenge reflects a fundamental issue within digital project management systems: the difficulty of adapting to the diverse nature of construction practices. The assumption that each element can be individually tagged and tracked is sometimes impractical, especially with bulk material or prefabricated elements designed for mass use, which lack individual differentiation. This scenario highlights the need for digital systems to evolve and accommodate the non-unique nature of many construction resources to enhance tracking accuracy and project management efficacy.

While the use of tracking technologies like radio-frequency identification (RFID) tags could potentially improve the management of non-unique construction elements, this approach might introduce operational inefficiencies. For instance, the requirement for construction personnel to locate and use a specific component based on its predetermined location allocated to its RFID tag, rather than using a similar item that is readily available and closer to the point of use, could slow down the installation process. This highlights the need for a balanced approach that optimizes the benefits of advanced tracking technologies without disrupting the practical dynamics of construction workflows. Further research is essential to develop adaptive algorithms that can integrate these technologies effectively, enhancing operational efficiency without compromising the flexibility needed at construction sites. This calls for a nuanced understanding of onsite logistics and careful consideration of how digital systems like the WBPMS can be refined to address these challenges effectively.

3.7 Summary

In conclusion, this chapter presented a WBPMS framework for automating construction progress reporting across the design, fabrication, and construction stages of a building project by leveraging BIM as the central repository of project information. The application of the WBPMS to piling activities within a construction project has not only validated the proposed framework but also demonstrated its capability to replicate traditional progress reports with increased precision and reduced human intervention. This advancement addresses critical industry challenges, particularly the misalignment between technological capabilities and the operational requirements of industry professionals.

A key feature of the WBPMS framework is its ability to establish robust links between BIM elements and corresponding project documentation, which is crucial for tracking progress through the various stages of a project's lifecycle. This framework automates the process of retrieving document statuses and synchronizes them with stage codes embedded in BIM elements, significantly streamlining the progress monitoring and reporting workflow. This automation not only enhances accuracy but also reduces the time and effort traditionally required for manual updates.

While the WBPMS framework effectively leverages existing construction documentation to track project progress, it also underscores limitations. These include its reliance on single search terms, the constraints posed by data availability within digital systems, human errors during data entry into digital systems, and the challenges in tracking non-unique elements such as prefabricated piles which lack distinct identifiers. Despite systems such as CDEs providing the structured data essential for WBPMS operations, these limitations highlight the need for improved data management practices and system adaptability. It also highlights the need for more robust inspection systems for more reliable inspection results that can be used to infer progress. Addressing these challenges is essential for fostering widespread standardization and enhancing the reliability and efficiency of progress monitoring across the construction industry.

Despite these challenges, this research highlights the significant potential of BIM and digital management systems to meet the practical needs of construction professionals, effectively bridging the gap between advanced technological capabilities and on-ground requirements. The hesitancy in adopting these technologies is often due to the lack of skilled personnel, awareness, and standardization within the industry. Addressing these barriers through dedicated education, training, and the development of intuitive, user-friendly systems is critical for enhancing industry-wide adoption and standardization, ultimately improving efficiency and accuracy in construction project management.

Future research should focus on refining the WBPMS framework to overcome the identified limitations, such as the integration of Large Language Models (LLMs) to enhance database search functionalities, which could significantly improve the precision and efficiency of data retrieval processes. Additionally, expanding the adaptability of the WBPMS across different construction project types and elements will be crucial for broadening its applicability in various construction contexts. Further studies should also explore the development of advanced tracking mechanisms for non-unique elements and investigate the potential integration of other innovative technologies like automated inspections, machine learning and IoT (Internet of Things) to enhance the real-time monitoring and management capabilities of construction projects. Lastly, more in-depth research is required to enhance current inspection systems, such as studying the possible automation of inspections to reduce human errors involved in the inspection process, which will be further discussed in subsequent chapters.

Chapter 4
Bridging automated inspections for automated construction progress monitoring

4.1 Introduction

The previous chapter outlined a framework designed to harness data from various construction processes to accurately reflect progress in accordance with industry practitioners' requirements. This framework functions effectively with structured data, irrespective of the source. Typically, reported progress needs validation by third parties through inspections or records of work completed. The WBPMS addresses this by using document statuses as a verification method for work done. However, these verification methods, often manual, can be subjective based on the third-party validators' experience and disposition.

In the previous chapter, we identified a few issues related to the use of inspection statuses that resulted in unreliable progress being reported, highlighting not only systematic issues within the conventional construction process but also common errors that were due to human intervention. The conventional inspection workflow is presented in Figure 18, with indications on the steps errors were encountered during the application of the WBPMS for construction stage monitoring. These include (1) human errors when creating the inspection forms, resulting in inaccurate information retrieval; (2) missed-out elements from inspections where inspection records could not be found; and (3) digital system limitations where the approved date of inspection could not be retrieved from the database.

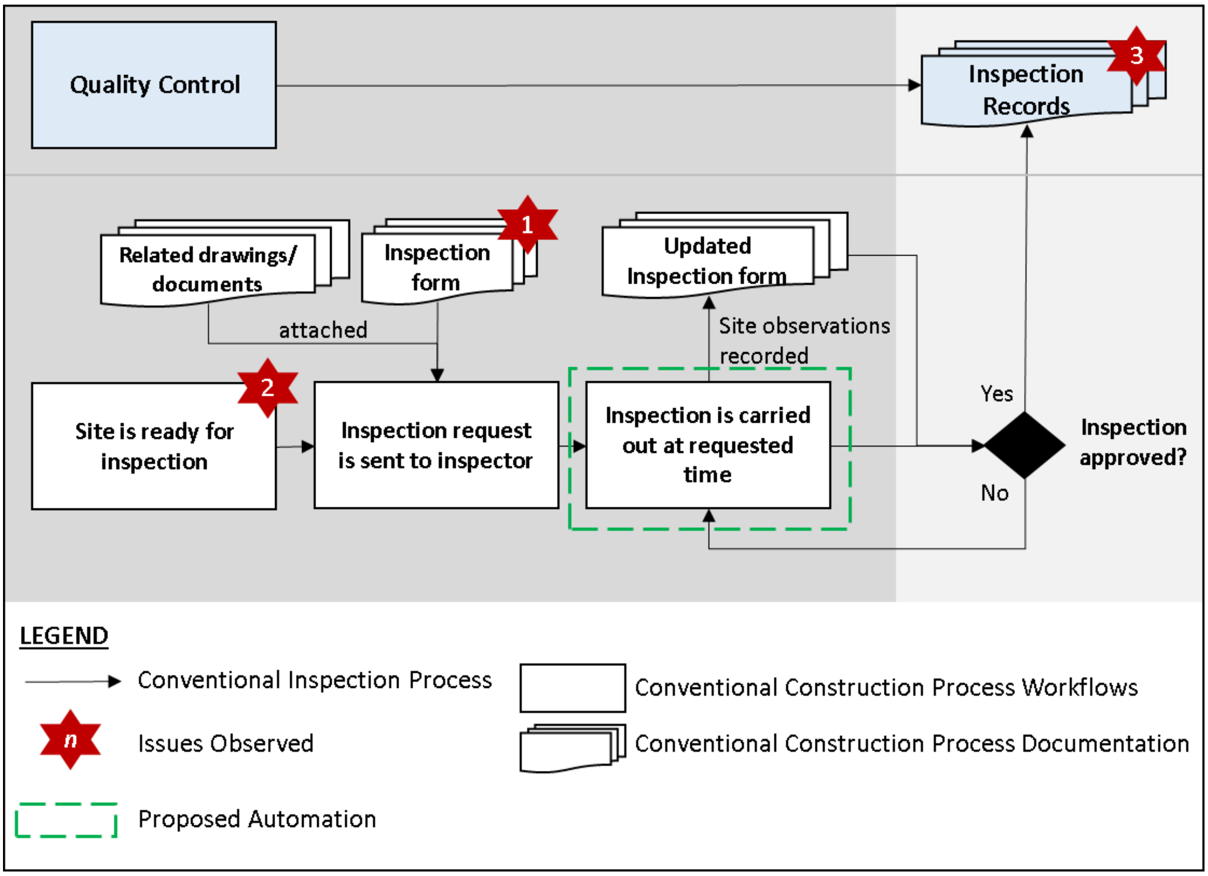


Figure 18. Overview of a conventional inspection workflow

By automating the construction inspection process, there is a possibility to eliminate the human errors involved in identified issues 1 and 2 (Figure 18). Whereas issue 3 would require database standardization of information requirements as discussed in the previous chapter. Thus, the objective for automating construction inspections is to first eliminate the human errors involved so that inspection results statuses would be more reliable. This can be achieved by eliminating the manually prepared inspection forms by having element-based inspection forms prepared, together with automated compliance rule checks, which are then validated by an authorized inspector. As a result, automated inspection records would also be generated. The theoretical concept of how automated inspections can be achieved as described is presented in Figure 19.

While there is a possibility to also automate construction inspections by processing the as-is data that computer-vision-based ACPM technologies used that were discussed in Section 2.1.1, these technologies have yet to demonstrate their ability to fulfil the dual roles of progress verification and compliance inspection required by third parties. This limitation underscores the necessity for technologies that operate beyond single-function silos. It emphasizes the need for further research into methods that integrate automated inspection results with the WBPMS, enhancing the reliability and objectivity of ACPM by ensuring that inspections and progress monitoring are seamlessly connected.

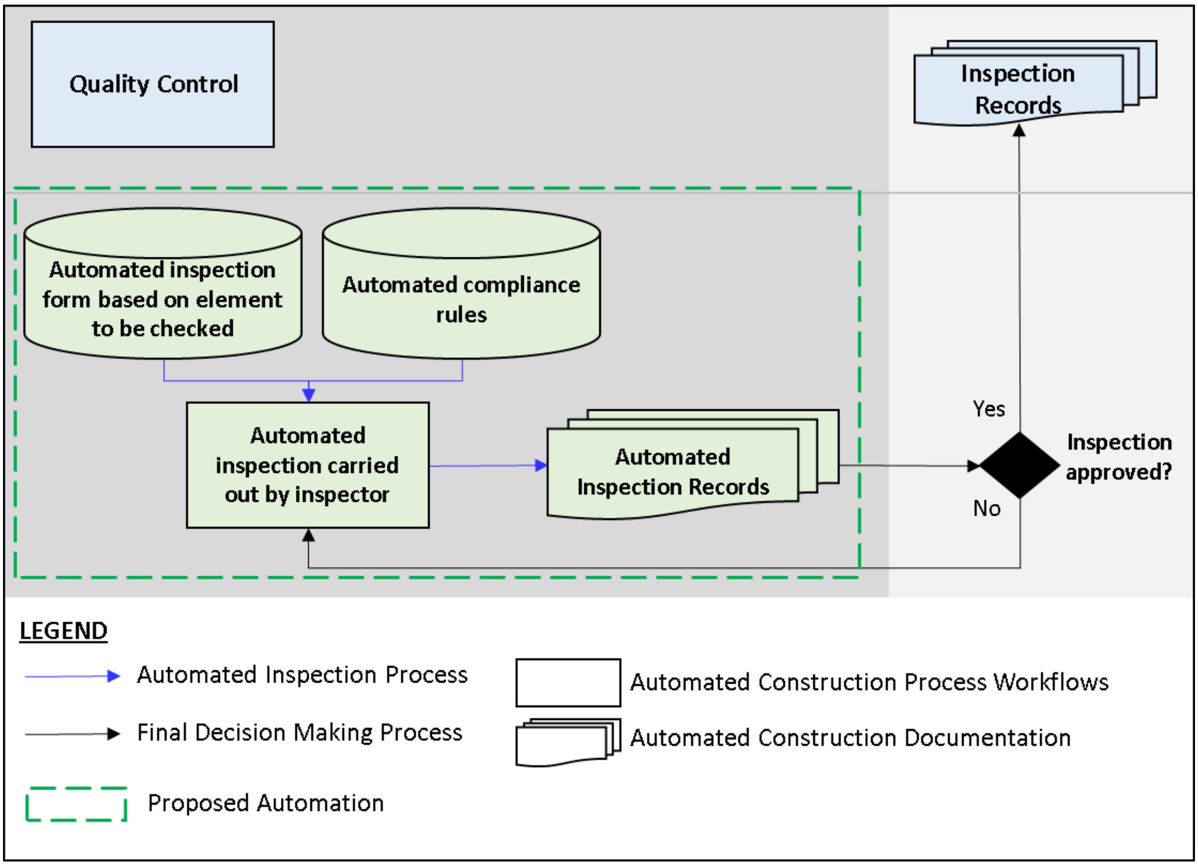


Figure 19. Theoretical concept of an automated inspection process

Thus, this chapter delves into these challenges, detailing the subjective nature of current verification practices and the limitations of existing technologies. It then explores emergent technologies suitable for bridging these gaps, potentially revolutionizing ACPM by enabling comprehensive, automated inspections where results are compatible with progress monitoring frameworks, thereby ensuring more consistent and reliable ACPM outcomes.

4.2 Limitations of current inspection methodologies

To identify methods that may bridge the gap between the WBPMS and automated inspections, it is essential to first recognize the limitations inherent in current inspection methodologies. These limitations not only affect the efficacy of traditional inspection processes but also highlight the need for a more integrated and automated approach to enhance construction project monitoring and compliance verification.

4.2.1 Compliance and accuracy challenges

Manual compliance checking in construction is often error-prone and time-consuming due to the complexity of regulatory standards and the necessity for frequent updates to these standards (Dimyadi, et al. 2016). Inspectors must remain updated on regulatory changes, which often requires them to memorize extensive data or consult regulatory guides during inspections, potentially slowing down the process. As highlighted in Table 1, staircase dimensional requirements vary widely across different countries' standards. Within a single country, variations in regulatory standards can be significant, as demonstrated in Table 12, which presents the evolution of dimensional requirements over the years, across different regulatory standards. This variance highlights the complexity of determining the applicable version of regulations for specific inspection items. For example, inspectors might encounter building development plans approved in different years but completed simultaneously, each adhering to different regulatory versions. This scenario complicates inspections, as inspectors need precise knowledge of the applicable standards based on the project's approval year, alongside the specific functional requirements of each building component, such as staircase widths varying by use and design criteria. Such complexities often require inspectors to rely heavily on information provided by designers or builders for compliance verification. Nonetheless, emerging technologies offer the potential to reduce errors and improve the efficiency of inspections (Zhong, et al. 2012), thereby improving the quality of inspection statuses used to infer progress within the WBPMS framework. This advancement could improve how inspection data integrates with automated progress monitoring systems, ensuring more precise and reliable progress tracking across construction projects.

4.2.2 Subjectivity and data integration challenges

Current traditional methods involving the use of basic construction tools rely heavily on human judgment, leading to inconsistencies and a lack of standardization across inspections (Atkinson 1999). This subjectivity can lead to corruptive practices, where inspectors might overlook non-compliance in exchange for bribes, resulting in project delays, poor workmanship, and the use of sub-standard materials. These factors compromise the overall quality and integrity of construction projects (Soni and Smallwood 2024). Moreover, the variability among inspectors in defining what constitutes "acceptable" or "completed" work can lead to inaccuracies in defining inspection statuses and thus, progress monitoring statuses, affecting the reliability of systems like the WBPMS. This calls for a more standardized and objective approach to inspections to ensure uniformity and accuracy in data used for progress monitoring.

Table 12. Updates to staircase regulatory dimensional requirements in Singapore

Design Parameter	Universal Design Guide 2016[1]	Universal Design Guide 2022[2]	Accessibility Code 2019[3]	Approved Document V7.03[4]	Approved Document V7.05[5]	Fire Code 2018/2023[6]
Max. riser height	150 mm	150 mm	150 mm[c]	175 mm[e]	175 mm[e]	175mm
Min. tread width	300 mm	300 mm	300 mm[c/d]	275 mm[f]	275 mm[f]	275 mm[f]
Min. stair width	1200 mm[a]	Not specified[b]	900 mm	900 mm	1000mm	1000 mm[f]
Min. headroom	2000 mm	Not specified[b]	2000 mm	2000 mm	2000 mm	2000 mm

[1] Universal Design Guide for Public Places (2016)

[2] Guide to Universal Design Index (2022)

[3] Code on Accessibility in the Built Environment 2019

[4] Singapore's Building Construction Authority Approved Document V7.03 (December 2022)

[5] Singapore's Building Construction Authority Approved Document V7.05 (March 2024)

[6] Code of Practice for Fire Precautions in Buildings was updated in Aug 2023 without changes to staircase dimensional requirements

[a] Applicable to public staircases

[b] Specified to comply with relevant codes

[c] Applicable to stairs for ambulant disabled

[d] Outdoor stairs require a minimum tread width of 350 mm

[e] Heights shall be of uniform height and size, where a tolerance of 5mm between two consecutive steps in any flight of staircase is acceptable

[f] Varies depending on building type - dimension shown is for general public stairs

Apart from the inherent subjectivity, manual inspection processes are time-consuming, subjective and error-prone (Xu, et al. 2021). Even though digital inspection forms can alleviate some of these challenges, they are still vulnerable to human errors during data entry, as highlighted in Chapter 3. While inspectors may be educated to input data systematically to avoid data integrity issues, occasional human errors may occur that affect the reliability of progress updates in the WBPMS. Martinez et al. (2020) presented an automated vision-based inspection for offsite production of light-gauge steel frames, highlighting that such automation could replace manual quality control activities, significantly reducing human errors, enhancing data accuracy, and achieving real-time quality assessment of production processes. This suggests that automating inspections with advanced technologies could potentially introduce a systematic approach to data entry where the results of the inspections could be integrated with advanced digital tools and platforms.

While vision-based inspections may be suitable for deployment in controlled factory environments, data acquisition in construction sites requires more flexibility due to the dynamic nature of construction sites. Emerging technologies like MR present an opportunity to bridge these gaps. MR can provide the flexibility of gathering data and processing data on edge, and it allows users to visualise data as it is being captured. Automating the inspection process and integrating results with the WBPMS can reduce the subjectivity and variability in data collection, paving the way for more reliable and consistent progress monitoring across construction projects.

4.3 Limitations of vision-based technologies for inspections

Section 2.1.1 identifies that vision-based technologies for ACPM have limitations due to the need for extensive training datasets, high computational demands, and susceptibility to occlusion issues, which compromise their ability to assess progress accurately. Moreover, these technologies are designed primarily for progress assessment and do not simultaneously perform quality inspections. Given that inspection for quality and work done verification are necessary processes to ensure compliance, the singular functionality of current ACPM research adds another layer of technological complexity to the monitoring process, making it challenging for construction personnel to operate these tools (Newcomer, et al. 2019). Furthermore, difficulties in integrating ACPM technologies with existing construction processes and technologies exist (Zhang, et al. 2022). Thus, the simplicity and broader scope of manual inspection and verification methods that rely on the expertise of the inspector remain predominant in the industry (Samsami 2024).

While leveraging vision-based technologies for inspections might seem efficient as the same images, footage, or point clouds used for ACPM can be analysed for quality checks, they face similar challenges. These include the lack of specific training datasets tailored to particular inspection tasks (Choi, Ha and Lee 2023), the necessity for high computational power (Zhao, et al. 2024, Choi, Ha and Lee 2023, Qureshi, et al. 2024), and additionally, the requirement for high-resolution data to ensure precision in quality assessments (Qureshi, et al. 2024). Due to the high computational demand, inspection analysis is typically performed after data acquisition rather than in real-time, leading to difficulties in obtaining more data if they are deemed necessary (Zhang, et al. 2022). Real-time data analysis instead involves manual analysis, such as manually identifying defects from a video frame (Dorafshan, Thomas and Maguire 2018).

Despite these challenges, the potential for technological advancements such as MR offers new opportunities for integrating real-time inspection capabilities with results potentially compatible with the proposed WBPMS systems due to its compatibility with BIM integration. MR technologies can potentially overcome the limitations of current vision-based systems by providing more interactive and immersive ways to conduct inspections without compromising on computational methods. The capabilities of MR highlight how the technology can bridge the gap between traditional inspection methods and modern digital approaches, paving the way for a more integrated and automated construction monitoring process.

4.4 Technological opportunities of MR technology

4.4.1 Technical compatibility with BIM

As discussed in Chapter 3, progress reporting deliverables include data and location-based plans. Data compatibility with BIM bridges the gap in generating such deliverables since design plans originate from BIM. MR can integrate seamlessly with BIM by identifying spaces using augmented data from BIM through devices like the HoloLens. This integration enables real-time visualisation and allows inspectors to compare design information with actual structures, enhancing the accuracy and efficiency of identifying discrepancies (Nguyen, et al. 2021). Inspections conducted in MR can be easily integrated with BIM to achieve efficient progress and issue-tracking (Holzwarth, et al. 2021).

On the other hand, vision-based technologies often rely on post-processed static images or videos to conduct inspections or assess progress. While these methods have proven successful to certain degrees, they lack MR's capabilities to interact with data directly compatible with BIM.

4.4.2 Immersive visualisation and data-driven inspections

Sensors on headsets can capture and process data in real-time, which can be visualised directly within the headset, thereby removing the subjective nature of inspections as results are computed based on sensor data rather than the subjective assessments of inspectors. This ability to visualise data in the context of the actual item being inspected helps inspectors verify data more intuitively and accurately (Aguero, et al. 2020). Such integration of AR within these headsets also enhances the inspection process by superimposing digital information onto the physical environment, providing inspectors with additional context and information that can lead to more informed decisions and actions. Not only does it allow inspectors to immediately see and address issues without the need for cross-referencing plans or documentation, but it also allows for a more comprehensive understanding of the inspected elements, enabling inspectors to identify potential issues or discrepancies that might not be evident through traditional methods (Athanasiou and Salamone 2020).

Furthermore, a user-interactive approach may give stakeholders more confidence in the inspections than AI-generated results, especially considering AI inspections are still in their infancy. The interactive nature of MR technology enables a more collaborative inspection process, allowing multiple stakeholders to view and interact with the same data in real time. This ensures consistency and transparency in the evaluation process.

4.5 Summary

In conclusion, while MR is a promising tool for achieving the inspection automation concept presented in Figure 19, offering several potential benefits; it is crucial to first establish the fundamental feasibility of using this technology effectively. Before exploring the advanced capabilities of MR, such as collaborative inspections, a study must first be conducted to understand how well it can perform basic inspection tasks.

Thus, the next chapter will explore the feasibility of using sensor data from MR to conduct dimensional checks against regulations. This foundational study sets the stage for future research into more complex applications of MR in construction inspections that can give reliable inspection data.

Chapter 5
MR inspection automation using scene understanding

5.1 Introduction

Chapter 3 introduced a framework for semantic enrichment of BIM for automated progress reporting utilising statuses of information transactions inherent in a construction project, and Chapter 4 discussed the need for integration of technologies to enhance automated construction progress monitoring with automated inspections, highlighting the potential of MR to achieve such automated inspection. This chapter will expand on that foundation by exploring an automated digital inspection approach, where the results of such inspections could be directly integrated into the WBPMS's status parameters to infer progress accurately. This process is indicated within the green box in Figure 1. Automated digital inspections aim to reduce the subjectivity and human errors associated with manual inspections, thereby enhancing the reliability and efficiency of the construction monitoring process. This integration promises to streamline the inspection process and improve the precision of progress assessments.

This study aims to automate quality inspections by employing MR devices for dimensional checks on corridors and staircases, a common inspection item to check for headroom and corridor clearances for authority compliance. This chapter first reviews commercially available scanning technologies and MR devices' capabilities. Subsequently, the viable logic for data analysis to automate inspection is presented. Lastly, the application of this technology is demonstrated through trials conducted by industry professionals. The outcomes of these inspections are then evaluated to assess the effectiveness of using MR devices in practical construction environments.

5.2 A comparative study of scanning technologies

While this study focuses on the use of MR devices for inspections, various scanning technologies have been developed, each offering unique benefits and limitations. A comparative analysis of these technologies, focusing on their applicability in real-world construction inspection scenarios, is discussed in this section to identify the most effective tools for specific types of construction inspections. The comparison will be made by examining the technical specifications, operational efficiencies, and practical outcomes of technologies such as Simultaneous Localization and Mapping (SLAM), the primary scanning technology available to MR devices, Light Detection and Ranging (LiDAR), and Structure from Motion (SfM) technologies. The most effective tool for specific types of construction inspections is then identified.

5.2.1 LiDAR and SLAM technology

LiDAR is a mapping technology that uses laser light to measure distances, creating fast, accurate, and reliable geometric representations of environments consisting of points. It is particularly useful for data acquisition on the as-built status of buildings and construction sites during construction-operation phases (Oh, et al. 2019). LiDAR scanners can be broadly classified into terrestrial scanners and mobile scanners (Lim, et al. 2013). The range and accuracy that scanners can achieve depend largely on the power, quality and pulse duration of the laser used by the hardware and the reflectivity and distance of the target surface. In general, the denser the point cloud obtained, the more accurate a model will be, but processing time would increase due to the large amounts of data acquired. Terrestrial scanners register each scan, superimpose and geolocate each scan, using either its built-in Inertial Measurement Unit (IMU), external markers, GPS, or a combination of these methods to produce an aggregated point cloud model of the scanned space. They rely on a line-of-sight principle to acquire data, where the scanners have to be moved around a space to ensure all corners have been captured. On the other hand, mobile scanners are typically handheld or mounted on drones or vehicles that can cover data acquisition over large areas more quickly than terrestrial scanners. Mobile LiDAR systems often integrate additional sensors, such as cameras, to accurately geolocate and register the point clouds while in motion using the SLAM technique.

SLAM is a technique for constructing spatial maps of an unknown environment while simultaneously keeping track of the sensor’s positioning in real-time, also known as localisation (Thrun and Burgard 2005). It consists of two parts, mapping and localisation, where a map is needed to localise the sensor’s position, and the sensor’s position is required to create the map (Taheri and Xia 2021). Advancements in SLAM technology have enabled real-time operation in diverse environments that integrate visual and inertial data for improved accuracy (Campos, et al. 2021). Nonetheless, due to the complexity of managing data from multiple sensors simultaneously, accuracy may be compromised compared to terrestrial laser scanners. Notable commercially available mobile scanning devices that utilize SLAM exist, such as the GeoSLAM ZEB Horizon RT Mobile Scanner (FARO 2024), FARO® Orbis™ Mobile Scanner (FARO 2024), NavVis VLX 2 (NavVis 2024) and Leica BLK2GO (Leica Geosystems 2024). These devices typically use LiDAR scanners as the sensors, whereas depth sensors are used with MR devices for spatial mapping. This is further discussed in Section 5.3. Summaries of the technical specifications of terrestrial and mobile scanning devices are presented in Table 13 and Table 14, respectively. Table 14. Mobile scanning devices specificationsWhile it is worth noting that mobile scanners can achieve up to 5 mm accuracy as compared with the 1.9 mm accuracy of terrestrial scanners, the cost of both technologies is upwards of USD$50,000, which can be considered a significant investment as opposed to the cost of a simple tape measure that is conventionally used during inspections. Additionally, skilled manpower is required to post-process the acquired data before it can be used for downstream purposes such as dimensional compliance checks.

Conversely, while the depth-sensing technology available on MR devices does not achieve the same accuracy as mobile or terrestrial LiDAR scanners, the lower initial investment and reduced complexity of MR applications may lead to broader adoption of MR technology.

5.2.2 SfM technology

The SLAM technique relies on sensor data for creating spatial maps and is primarily employed where an agent needs to navigate and map the environment simultaneously. The SfM technique reconstructs a 3D scene from image sequences by extracting and matching features between images, as well as estimating the camera's motion (Özyeşil, et al. 2017). Since this technique relies on still images for reconstruction, a highly accurate model can be reconstructed if camera positions are known, for example, by using ground control points and positioning technologies such as Global Navigation Satellite System (GNSS) (Zhao, et al. 2021). Nonetheless, this methodology might not be suitable for the specific inspection use case of dimensional quality inspection as sufficient images have to be captured (Róg and Rzonca 2021) for the reconstruction of each object that needs to be inspected to sufficient accuracy.

Thus, due to MR devices' mobility, price, and real-time spatial mapping capabilities, MR technology will be further investigated for the specific use case of dimensional compliance checks.

Table 13. Terrestrial scanning devices specifications

Hardware	FARO Focus S150	Leica RTC360	Trimble X7
Display	• Via iOS/Android tablet	• Via iOS/Android tablet	• Via Trimble T10 tablet
Laser class/wavelength	• Class 1, 1550 nm	• Class 1, 1550 nm	• Class 1, 1550 nm
Camera	• 13 MP camera	• 3-camera system, 36 MP	• 4 x coaxial 10 MP camera
Range	• 100 m	• 130 m	• 80 m
Accuracy	• 2 mm @ 10 m, 3 mm @ 25 m[1]	• 1.9 mm @ 10 m, 2.9 mm @ 20 m, 5.3 mm @ 40m	• 2.4 mm @ 10m, 3.5 mm @ 20m, 6.0 mm @ 40 m
Scanner points per second	• 1,000,000	• 2,000,000	• 500,000
Scan duration	• No data available	• No data available	• Fastest 2 min 34 sec with images, 1 min 34 sec without
Weight (w/ batteries)	• 4.4 kg	• 6 kg	• 5.8 kg
Size	• 23 x 18.3 x 10.3 cm	• 12 x 24 x 23 cm	• 17.8 x 35.3 x 17 cm
Battery life	• 4.5 hours	• Up to 4 hours	• 4 hours
Retail price (package)	• Approx. USD$63,000[2]	• Approx. USD$70,000[2]	• Approx. USD$59,000[3]
Post-processing software	• FARO Scene	• Cyclone Register	• Trimble Business Center
Remarks	-	• Real-time registration possible	-

[1] For white surfaces at 90% reflectivity

[2] Price obtained from a reseller in Singapore in 2020 and calculated at an exchange rate of 1 USD : 1.35 SGD

[3] Price obtained from a resller in Singapore in 2024 and calculated at an exchange rate of 1 USD : 1.35 SGD

Table 14. Mobile scanning devices specifications

Hardware	GeoSLAM ZEB	FARO® Orbis™	NavVis VLX2	Leica BLK2GO
Display	• Not available	• Via wireless smartphone connection	• Built-in display	• Via wireless smartphone connection
Sensors	• Velodyne Lidar[4] • 1 x IMU	• 32-channel LiDAR • 1 x IMU	• 2 x Velodyne Lidar[1] • 1 x IMU	• dual-axis LiDAR • 1 x IMU
Camera	• Available as an add-on kit	• 8 MP 360° camera	• 4 x 20 MP fisheye camera	• 3-camera system, 4.8 MP 300° x 135° • 12 MP, 90° x 120°
Range	• 100 m	• 120 m	• 50 m	• 25 m
Accuracy	• 10 - 30 mm relative accuracy	• 5 mm	• 5 mm local accuracy	• 10 mm @ 2-min scan duration in controlled environment
Scanner points per second	• 300,000	• 640,000	• 2 x 1,280,000	• 420,000
Weight (package)	• 2.9 kg	• 3.6 kg	• 8.7 kg	• 775 g
Size	• 46 x 37 x 18 cm[5]	• 50 x 62.5 x 25 cm[2]	• 109 x 33 x 45 cm	• 27.9 x ⌀0.8 cm
Battery life	• 90 Wh	• Typical 3 hours	• 2 x 90 Wh (1.5 hours)	• 45 to 50 mins
Retail price (package)	• Approx. USD$58,000[6]	• Approx. USD$58,000[7]	• Approx. USD$93,000[8]	• USD$55,575
Raw data file size	• 100-200 MB per minute	• 350 MB per minute	• Information not available	• Information not available
Post-processing software	• GeoSLAM Hub	• FARO Connect / FARO Sphere XG	• NavVis Ivion	• Cyclone REGISTER 360

[4] Velodyne Lidar, 2023. https://velodynelidar.com/automated-with-velodyne/ Accessed 9th June 2024.
[5] Size of carrying case – actual size unavailable as device is made up of several components
[6] Price obtained from a reseller in Singapore in 2020 and calculated at an exchange rate of 1 USD : 1.35 SGD
[7] Price obtained from a reseller in Singapore in 2024 and calculated at an exchange rate of 1 USD : 1.35 SGD
[8] Price obtained from a resller in Singapore in 2022 and calculated at an exchange rate of 1 USD : 1.35 SGD

5.3 A comparative study of MR devices

Due to the limitations of VR devices for onsite applications, only MR devices were considered for this automated inspection study. A comparative analysis of commercially available XR devices was conducted to identify the most suitable MR device. The study assessed the key specifications of five prominent MR devices as outlined in Table 15 (Alizadehsalehi, Hadavi and Huang, 2020, Li, et al. 2023, Alizadehsalehi and Hadavi, 2023). The Nreal Varjo is a tethered device that utilises VR passthrough to transit into an MR environment, allowing users to view the actual physical space via a camera (Varjo 2023). As such, this device is not suitable for on-site usage due to its limited mobility. Although the ODG R9 (ODG 2023) offers benefits in terms of weight and price, it has limited developer community support and commercial availability. The Magic Leap 2 emerges as a primary alternative to the HoloLens 2; however, its user accessibility is diminished due to the necessity of acquiring additional prescription inserts (Magic Leap Inc 2023), a factor that potentially limits its deployment for users requiring prescription eyewear. The Microsoft HoloLens 2 was ultimately selected due to spatial mapping capabilities, user support, and versatility, making it ideal for on-site inspections. This choice underscores the importance of device functionality and community support in deploying MR technologies for practical construction applications. Additionally, Lee et al. (2023) demonstrated MR's potential using the Microsoft HoloLens 2 for edge computing of staircase dimensions, showcasing high accuracy in vertical measurements such as headroom compared to ground truth data.

5.3.1 Microsoft HoloLens 2 hardware

Introduced commercially in 2019, the Microsoft HoloLens 2 is an advanced mobile AR Head-Mounted Device (HMD) that supports on-device processing. It uses visible light cameras for localisation and a depth sensor for spatial mapping. The depth sensor operates in the 'short throw' mode for objects within the range of 0 m to 0.8 m and the 'long throw' mode for objects within the range of 0.8 m to 3.5 m (Hübner, et al. 2020). The positions of these sensors on the device are indicated in Figure 20.

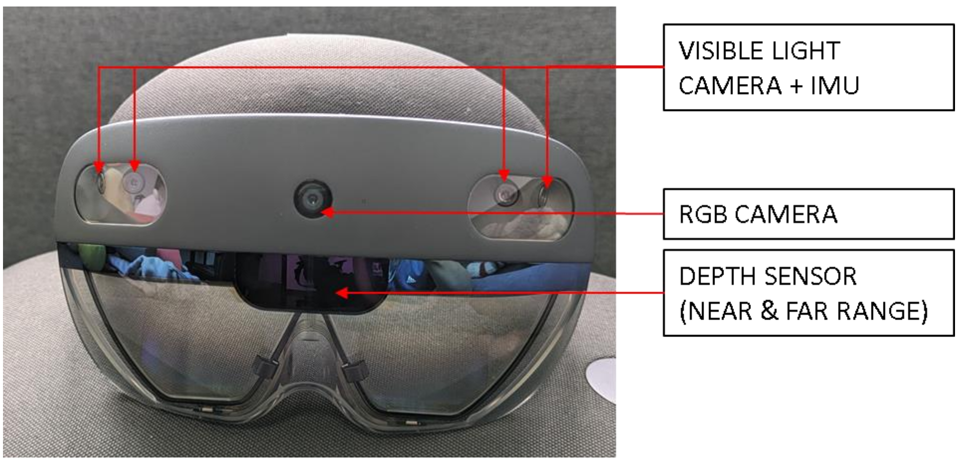


Figure 20. Microsoft HoloLens 2 sensors

5.3.2 Microsoft HoloLens 2 spatial mapping and scene understanding

In the context of the HoloLens 2, spatial mapping involves the creation of a virtual twin of real-world surfaces through 'Spatial Surfaces' represented as triangle meshes. These meshes allow users to interact within virtual spaces like tangible surfaces. As the device scans its environment, it updates these spatial surfaces in real time to reflect new environmental data accurately, thereby providing dynamic and responsive virtual interaction capabilities (Microsoft 2023). This feature is pivotal for applications requiring high levels of interaction with the virtual overlay in real-world contexts.

Scene Understanding in the Microsoft HoloLens 2 transforms unstructured sensor data from the environment into intelligibly labelled surfaces or SceneObjects, such as 'Wall', 'Floor', 'Ceiling', 'Platform', and 'Background'. This capability allows for a static query of spatial surfaces across an unlimited range once initialized (Microsoft 2022). The segmentation of these surfaces leverages Microsoft's custom-built processor, which includes Deep Neural Network (DNN) capabilities (Stachniak 2020), enhancing the device's ability to interpret its surroundings effectively. Notably, this advanced feature is exclusive to the HoloLens 2 and is not available on its predecessor (Microsoft 2022).

Several studies have assessed the indoor mapping capabilities of the Microsoft HoloLens. Notably, Hübner et al. (2019, 2020) determined a scale factor ranging from 0.9879 to 0.9887 when comparing HoloLens-generated meshes against a Terrestrial Laser Scanner (TLS) ground truth mesh, achieving an accuracy of up to 1.7 cm after scale correction (Hübner, et al. 2020). Additionally, Khoshelham et al. (2019) found that the HoloLens mesh had a local plane-fitting precision of 2.25 cm and a mean distance error of 5 cm compared to a TLS mesh. The larger errors observed may stem from the varying accuracies of point cloud registration across different TLS brands used in the studies.

While prior studies primarily utilized the original HoloLens, Terrugi and Fassi (2022) explored the use of the HoloLens 2 for mapping heritage environments. Their findings indicated that the HoloLens 2's accuracy varied with the environment: significant deviations occurred in large spaces beyond the sensor's 4 m range and in tight spaces closer than 0.5 m. Deviations were up to 0.59 m on XY horizontal planes and 0.1 m vertically in challenging areas, whereas, in human-scale spaces, maximum deviations noted were 0.05 m horizontally and 0.1 m vertically.

While previous research has primarily focused on obtaining accurate spatial maps using the HoloLens, these studies generally did not explore the potential applications of these maps, such as using them for dimensional inspection checks. This study, therefore, aims to investigate the capabilities of the HoloLens 2's scene understanding features for automated measurement of dimensions to ensure regulatory compliance. This involves evaluating how effectively the HoloLens 2 can compute spatial dimensions that adhere to required standards.

5.4 Proposed methodology

The MR application, the development of which is detailed in Section 5.2.1, is designed to compute measurements from meshes identified by the scene understanding SDK. Given the simplicity and ease of use of the traditional tape measure, the MR application is developed with a focus on user-friendliness and intuitive interaction. The effectiveness of this application will then be assessed by comparing the accuracy of MR-computed measurements against those obtained from tape measures, using design specifications as the benchmark for expected dimensions. This comparison aims to validate the precision of MR technology in performing dimensional checks for regulatory compliance.

Initial tests were conducted on a staircase flight at Osaka University, as shown in Figure 21, to assess the viability of an MR application in automating measurements. The environment was scanned in 1-minute increments, with a total duration of up to 5 minutes, to determine the impact of scanning time on accuracy. This duration was selected based on practical considerations: it would typically take less than a minute to navigate a flight of stairs, making prolonged scanning times impractical for real-world applications.

Before each scan, all previous spatial data were cleared from the HoloLens 2 to prevent interferences from previous scans. The scanning procedure began at the centre of the lower landing, facing the stairs. Scanning was done by ascending and descending the flight of stairs, continuously looking around until the set scanning time elapsed. After completing the scan, the application calculated the measurements, and the results were documented in a spreadsheet for comparison. For benchmarks, conventional tools were used. A steel tape measure was used to obtain staircase width and riser heights, and a laser measure was used for headroom measurements due to the longer distances involved.

Table 15. MR devices specifications

Hardware	**ODG R9** (ODG 2023)	**Microsoft HoloLens 2** (Microsoft 2023)	**Magic Leap 2** (Magic Leap Inc 2023)	**Nreal Varjo XR-4** (Varjo 2023)	**DAQRI Smart Glasses**
Year available	2018	2019	2022	2023	Discontinued (Alizadehsalehi and Hadavi 2023)
Display	• See-through lenses at 1080p	• See-through lenses at 2k resolution	• See-through lenses	• Dual 20MP passthrough camera	
Sensors	• Ultra-wide fisheye for tracking • Dual 5MP cameras for stereo capture and depth tracking	• 4 visible light cameras for head tracking • 2 infrared cameras for eye tracking • 1MP Time-of-Flight depth sensor	• 3 Wide-angle RGB cameras • 4 eye tracking cameras • Depth camera	• 300k pixel LiDAR	
Camera	• 13MP Camera, 1080 120fps or 4k 60fps	• 8MP RGB Camera, 1080p 30fps	• 12.6MP RGB Camera, 1080p 60fps or 4k 60 fps		
Weight	• 181 g	• 566 g	• 260 g	• 665 g + headband 356 g	
Battery Life	• 1400mAH	• 2-3 hours	• 3.5 hours	• N/A – Tethered	
Retail price	• USD$1,800	• from USD$3,500	• from USD$3,299	• from USD$3,990	
Availability	• Via request	• 36 countries	• 20 countries	• 41 countries	
Developer community/tools	• ODG Developer Centre	• Microsoft Learn • MR Community Hub	• Learn: Magic Leap 2 • Magic Leap 2 Developer Forum	• Varjo Developer	
Others	• Incompatible with prescription glasses		• Prescription lens insert possible • Tethered mobile compute puck	• Incompatible with prescription glasses	

Figure 21. Staircase flights used in experiments – Osaka University (Left), HFT1 L13 (Center), HFT1 B1 (Right)

After verifying the MR application's functionality, industry professionals were invited to test its accuracy and usability. Volunteers used both conventional tools (a steel tape measure for staircase width and riser height and a laser measure for headroom) and the HoloLens 2 to measure the same dimensions at selected staircases. Given the potential for error due to the typical sloping of staircase soffits, the experiment was also extended to include measuring the heights of two corridors in Singapore, as shown in Figure 22.

Figure 22. Corridors used in experiments – HFT1 B1 (Left), HFT1 L13 (Right)

Before beginning the experiments, each volunteer received a tutorial on how to use the MR application. For consistency in data collection, participants were instructed to start the scan facing the staircase from the bottom landing. They were required to ascend and descend the staircase twice to ensure comprehensive spatial data capture. Between each session, all hologram and spatial mapping data were cleared to prevent data overlap and ensure that each new scan started with a clean slate for accurate measurements. This standardization was crucial for comparing the results across different participants.

All dimensions captured during the experiments were recorded in a spreadsheet for analysis. Statistical methods were applied to evaluate the variability and accuracy of the MR application using the HoloLens 2 in comparison to traditional measurement techniques. A screen recording of each measurement session was captured for record purposes, and the spatial mesh generated during the scans was exported. Subsequently, a simple opinion survey was collected from each volunteer.

5.4.1 MR application development

The MR application for this study was developed in Unity (Unity 2023) utilizing the Mixed Reality Toolkit (MRTK) (Microsoft 2022) and the scene understanding Software Development Kit (SDK) (Microsoft 2022). The software architecture presented in Figure 23 (Stachniak 2020) demonstrates a high-level overview of the interactions between sensor data and the SDK. Scene understanding interprets the spatial mesh to predict which parts represent walls, ceilings, floors, platforms, backgrounds, etc. (Ong and Siddaraju 2017). The scene understanding SDK acts as a communication layer between the MR application and the scene understanding runtime, generating 'quads' that classify real-world surfaces into 'SceneComponents', which are categorized by their 'Kind' property – Wall, Floor, Ceiling, Background, etc. (Microsoft 2022). Each SceneComponent resides within a 3D coordinate system that can be queried. Automated computation of distances between categorized quads provides the as-built dimensions. Finally, the application instantiates game objects in the virtual space, enabling visual verification of measured scenes.

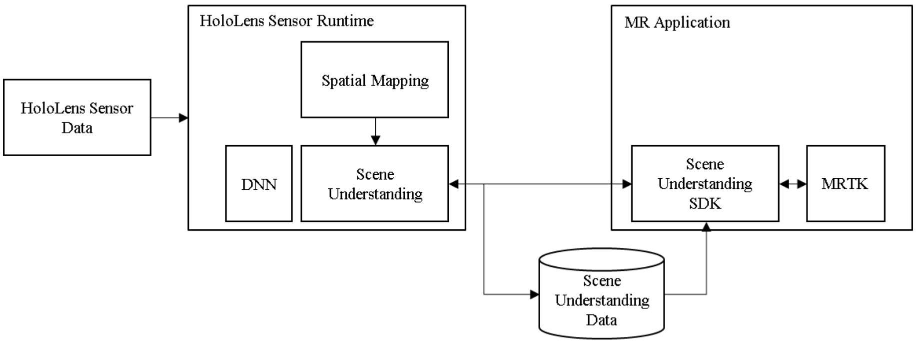


Figure 23. MR application software architecture overview

After acquiring the various computed dimensions, it facilitates compliance checks through a checklist customized for specific building types, as detailed in Table 1. This checklist varies - for instance, between residential and industrial buildings – due to different regulatory requirements. The application uses if-then logic to automatically confirm whether the measured dimensions comply with the relevant regulations. To accommodate potential internet connectivity issues at construction sites, the application allows users to export the checklist results as a .txt file, which is saved locally on the device, ensuring data is accessible and reliable regardless of network status.

An overview of the decision flow diagram described above is presented in Figure 24During application design, user actions are kept similar to the conventional method of acquiring, processing, and evaluating dimensional compliance, except for the user having to complete a checklist during data evaluation.

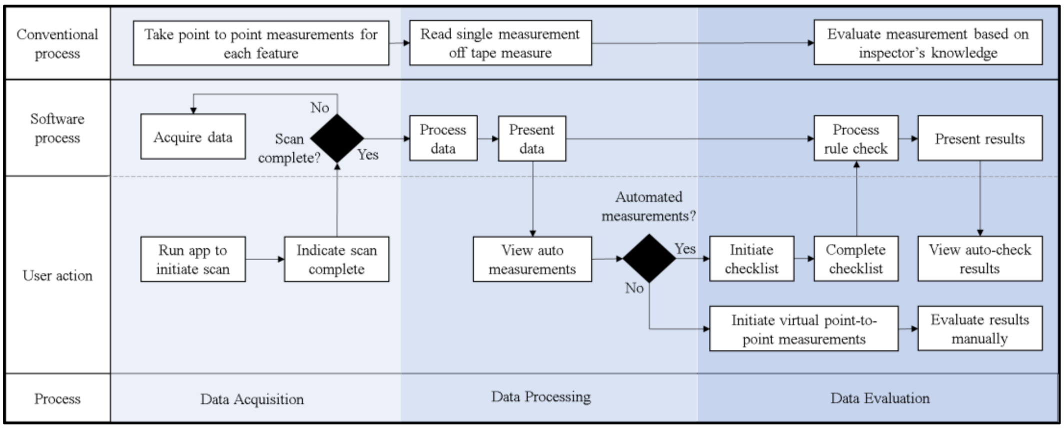


Figure 24. MR application decision flow diagram

5.4.2. Computing measurements in MR

The scene understanding SDK classifies surfaces based on orientation and size, which aids in accurately identifying various elements within a space. For instance, large flat surfaces like staircase landings are categorized as 'Floor' and vertical surfaces as 'Walls', shown in the application as green and red surfaces, respectively. Ceilings, whether sloped or flat, are identified as blue surfaces. However, smaller surfaces such as staircase treads are typically categorized as 'Background' due to their smaller size and spatial positioning. Thus, to accurately identify these treads, the application compares the vector normal of each quad with the vector normal of defined floors. Once treads are identified, they are visually distinguished as magenta surfaces, as shown in Figure 26.

Once the Scene Understanding SDK has categorized the quads based on the 'Kind' property, they are organized into lists for further processing. The list that includes quads identified as staircase treads is sorted by the height of each quad to facilitate the computation of measurements. To determine the longer side of each quad, game objects are positioned at the centre, leftmost, and rightmost extents of the quads, aligning precisely with the edges of each tread. This arrangement is critical for measuring headroom, which is the vertical distance from the pitch line—a straight line connecting the edges of the treads, as shown in Figure 25—to the soffit above.

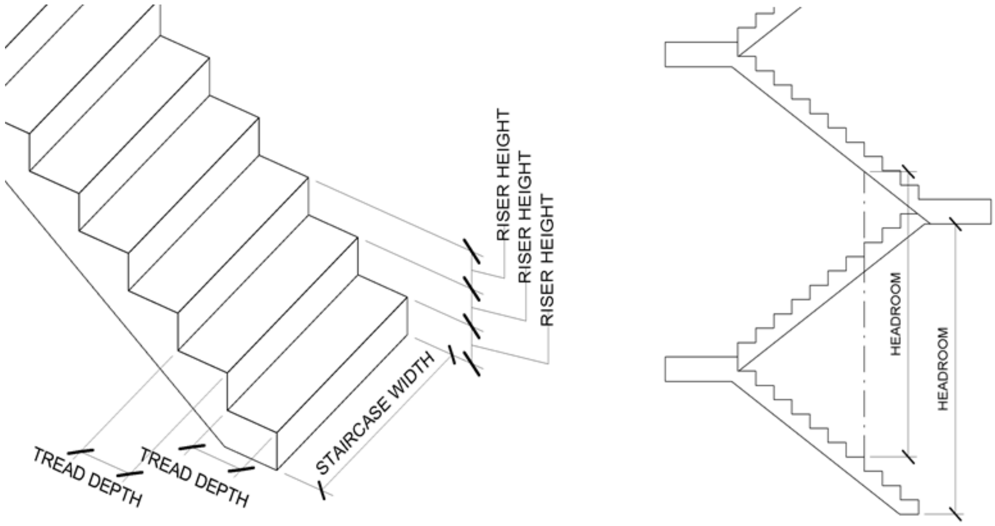


Figure 25. Typical staircase feature dimensions

The process begins with an iterative loop that calculates the riser heights by calculating the elevation differences between the centre markers of each tread. The widths are determined by the distances between the leftmost and rightmost game objects positioned at the edges of each tread. However, calculating headroom is more complex due to staircase soffits often being sloped. To accurately measure this, the 'Raycast' (Unity 2023) function from Unity is utilized, which projects a vertical ray from the rightmost game object to the ceiling quad, where it intersects. The distance of this ray, representing the headroom, is then recorded. These measurements are visually represented through game objects as depicted in Figure 26 and Figure 27, illustrating the comprehensive automation of staircase feature dimension computations.

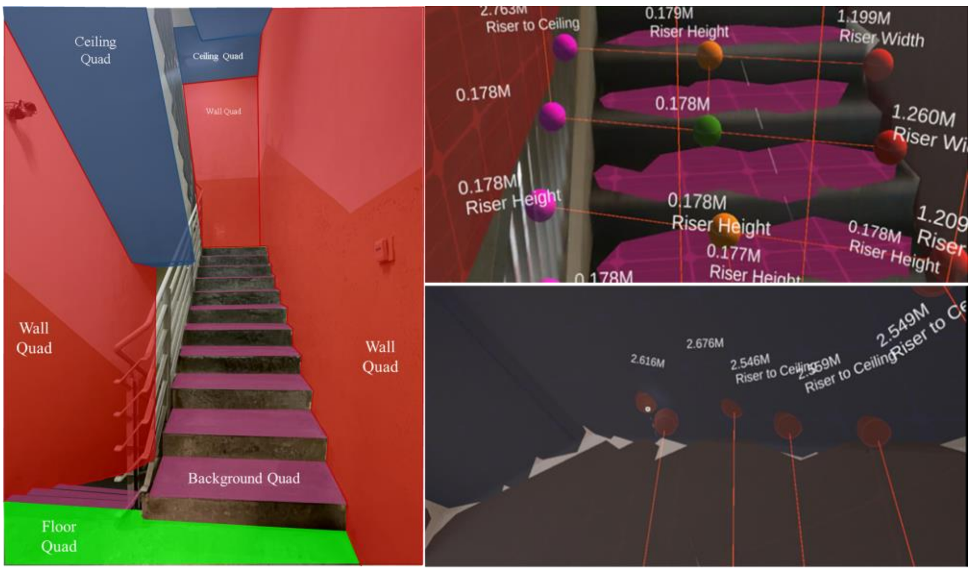


Figure 26. MR results for quad generation – Expected results (left); Actual results of Riser Height and Width (top right); Actual results of Headroom (bottom right)

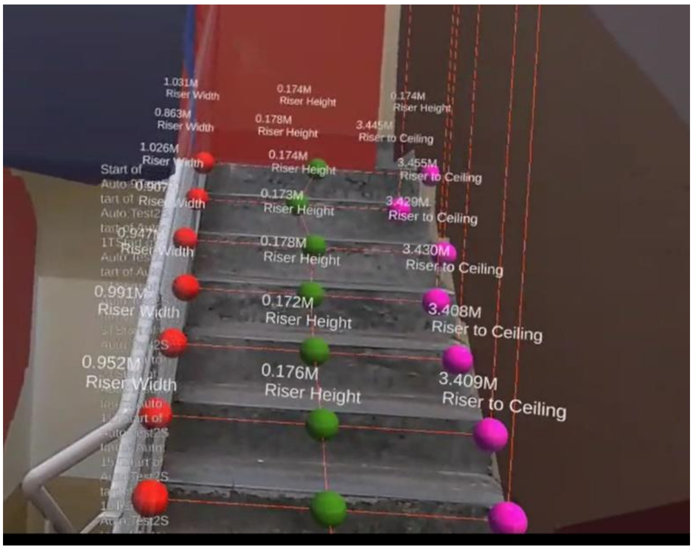


Figure 27. Overall view of staircase with automatically generated dimensions[9]

5.4.3 Rule-based compliance check

As a proof of concept, the application incorporates a checklist customized to adhere to regulations and guides specific to Singapore, such as the Singapore Building Construction Authority Approved Document (Building Construction Authority (Singapore) 2022), Singapore Universal Design Guide 2016 (Building and Construction Authority (Singapore) 2016), the Code on Accessibility in the Built Environment 2019 (Building and Construction Authority (Singapore) 2019), and the Code of Practice for Fire Precautions in Buildings 2018 (Singapore Civil Defense Force 2018). This checklist accounts for various factors such as building type, public access levels, usage by elderly people, designation as a fire escape route, and suitability for ambulant individuals. The MR-generated dimensions are evaluated based on these criteria. The checklist, shown in Figure 28prompts users to verify compliance with regulatory dimensional standards, highlighting any non-compliances, such as insufficient staircase width, in red to indicate areas requiring attention. This method does not require inspectors to remember the applicable building regulations offhand.

5.4.4 Opinion survey

Since the corridor measurements were relatively simple to acquire measurement data compared with the staircase, the volunteers were asked to complete separate opinion surveys using Google Forms on the ease of use of the conventional tools and the MR application and their perception of the accuracy and trueness of the results obtained from both tools. A qualitative evaluation is then provided.

[9] The background text visible on the left side of the figure is debug output, which is not integral to the application's core functionality or research findings.

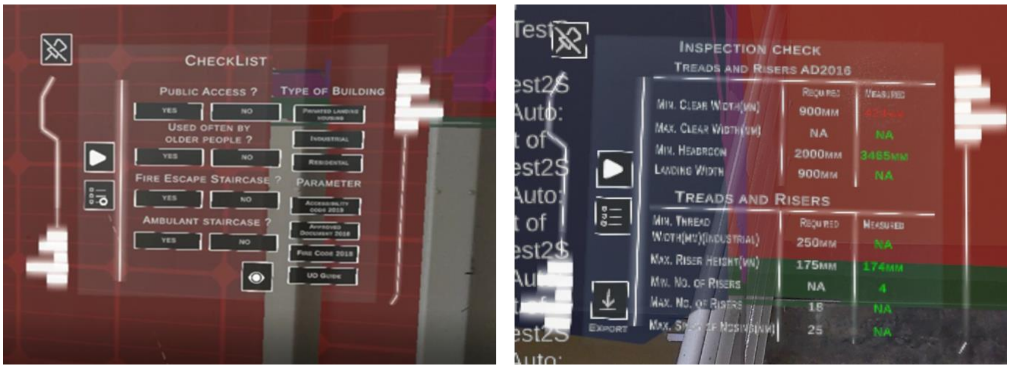


Figure 28. Regulatory dimensional compliance checks in MR – Checklist (left); Compliance check results (right)[10]

5.5 Results

5.5.1 Automatically computed staircase measurements against conventional measurements

The MR application underwent incremental development, with its first application on an outdoor staircase at Osaka University (Figure 21). The main aim was to obtain vertical riser height and headroom measurements automatically.

Riser height results are presented in Figure 29. Although previous studies with HoloLens meshes suggested a consistent scale factor of about 0.988 relative to TLS data (Hübner, et al. 2020, Hübner, et al. 2019), this factor accurately reflected measurements close to 175 mm but not for those around 180 mm. However, the validity of the scale factor for 180 mm measurements remains inconclusive due to limited MR data for riser heights of 180 mm. Figure 30 illustrates that a 4-minute scan duration yielded the highest number of automated measurements, yet no definitive correlation was found between scan length and measurement accuracy. The experimental series' reliability is somewhat limited by the fact that a single user conducted all measurements, preventing a determination of variability among different users' measurements.

[10] The background text visible on the left side of the figure is debug output, which is not integral to the application's core functionality or research findings.

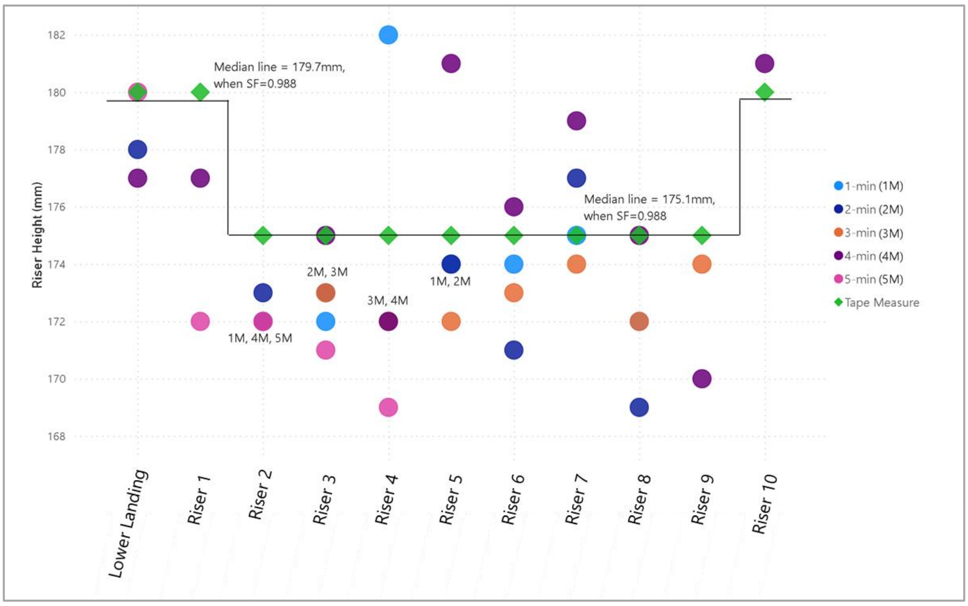


Figure 29. Distribution of measurements of riser height by location and scanning time – Osaka University staircase flight

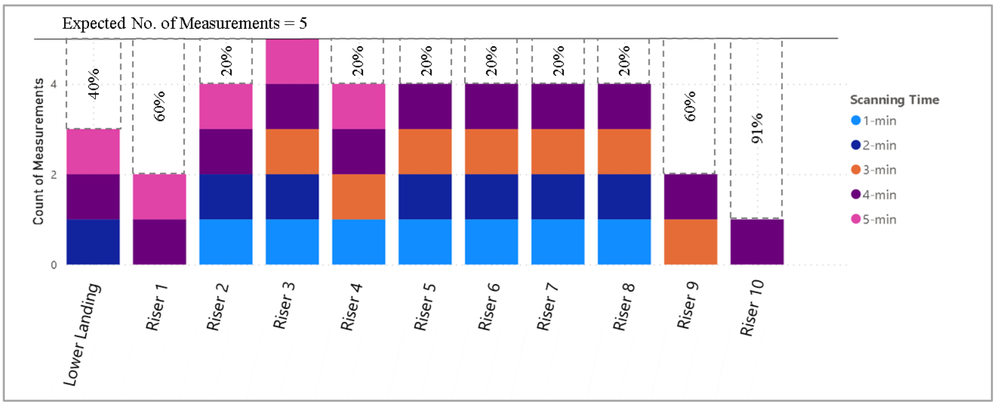


Figure 30. Occurrence of automated riser height measurements by scanning time – Osaka University staircase flight

Figure 31 presents the headroom measurement results, which indicate that while applying the scale factor aligns some automated measurements closer to conventional values, a consistent scale factor across various locations cannot be confirmed due to the limited data sample. The proximity of these measurements to the limits of the device's sensor range may explain the observed discrepancies. Notably, automated measurements for headroom were more reliably obtained in the first half of the staircase across all scan durations, as demonstrated in Figure 32. Consistent with the riser height findings, the 4-minute scanning duration consistently produced the highest number of accurate automated measurements. This pattern underscores the potential limitations of sensor range on measurement reliability in certain scenarios.

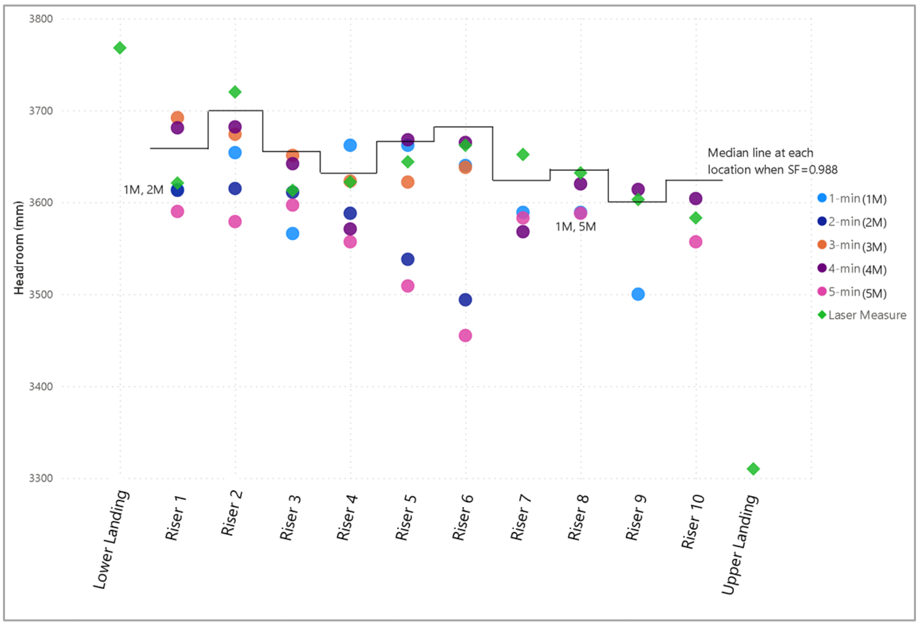


Figure 31. Distribution of measurements of headroom by location and scanning time – Osaka University staircase flight

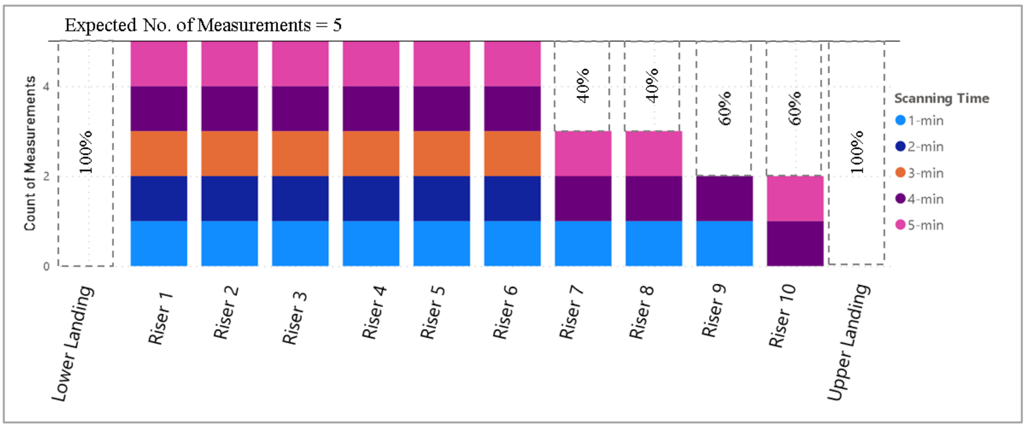


Figure 32. Occurrence of automated headroom measurements by scanning time – Osaka University staircase flight

The accuracy of automated dimensions in the MR application depends on the correct classification of meshes by the Scene Understanding SDK. If the meshes are not properly categorized, automated measurements cannot be performed, necessitating manual measurements to comprehensively complete the staircase dimensions. This reliance highlights the need for precise and reliable mesh categorization to fully leverage the benefits of automation in measuring staircase features.

Although spatial data was reset before each test to ensure no data carryover, the tests were conducted back-to-back without significant cool-down periods for the HoloLens 2, which might affect the device's performance. Notably, sensor data has been reported to stabilize after the device has been running for about 60 minutes (Hübner, et al. 2020). Therefore, the favourable results from the 4-minute scan may be attributed to the device's sensors reaching optimal operating conditions. However, as the HoloLens ran out of battery after this session and was recharged for the subsequent 5-minute test, the next set of results did not replicate the success of the 4-minute scan, though they still provided satisfactory headroom data. This suggests that the warm-up period might be critical for achieving the best measurement accuracy with the HoloLens 2.

Recognizing the limitations identified in earlier tests, particularly with mesh labelling inaccuracies by the Scene Understanding SDK, the MR application was enhanced to include a manual measurement feature. This new functionality does not rely on automated labels but utilizes mesh coordinate data alongside the Unity Raycast function to measure distances between manually selected points. Subsequently, this enhancement was tested on two separate staircase flights and two corridors approximately 5 meters in length at HarbourFront Tower One (HFT1) in Singapore, shown in Figure 22. The results are presented in the next section.

5.5.2 Experimental results by volunteers

The results from experiments conducted by five construction practitioner volunteers are analyzed in this section with key statistical indicators such as Mean Absolute Error (MAE) presented in Figure 33 and summarized in Table 16. These findings highlight the variability in the accuracy of MR-based measurements:

- Staircase Width: Exhibited the highest MAE, over 7%, indicating that MR technology might currently be unreliable for measuring staircase width within this setup.
- Headroom Measurements: Errors of around 5% were shown when measurements were near the device's sensor range limit.
- Other Measurements: Errors were 2% or lower in all other tested locations, suggesting that MR technology is potentially viable for these measurements under the right conditions.

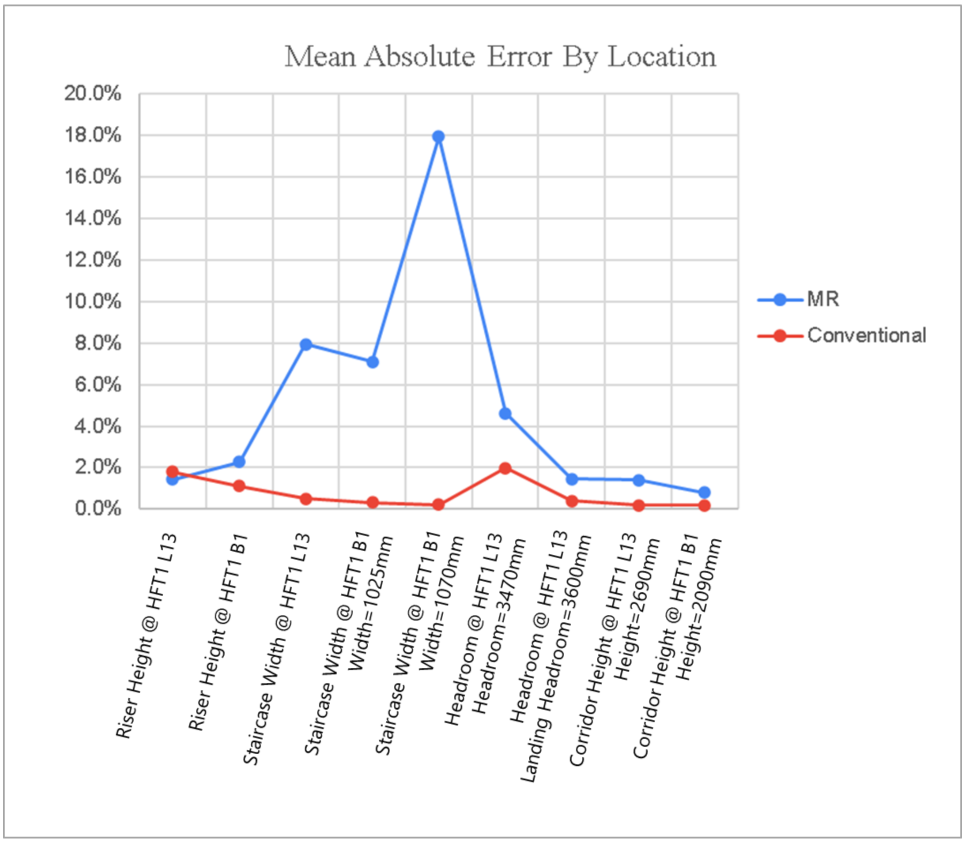


Figure 33. Mean absolute error of measurements by location

It is worth noting that results for B1's headroom could not be summarized as the soffit of the stairs was flat, resulting in varied headroom per riser. The distinct measurements reported by each user for each location are presented in Figures 34 to 41 for reference. The size of each marker represents the number of occurrences of each reported measurement. The bigger the marker, the more times that particular measurement was reported by each volunteer.

Headroom measurements were observed to have large variability at the HFTL13 staircase, presumably because the distance to be measured lies close to the sensor range. However, note that the conventional headroom measurements also demonstrate variability, likely due to human subjectivity when reading off a tape measure. Headroom measurements at the HFTB1 staircase were relatively consistent, but lower values were systematically reported than expected. Riser height values demonstrated similar variability between the MR measurements and conventional measurements. Meanwhile, the conventional method's staircase width measurements were largely consistent with the MR measurements. Notably, MR results were systematically reported to be larger than the expected measurements for headroom measurements at the corridors.

Table 16. Statistical evaluation of experimental results of MR measurements

Building Feature	Tool	Location	Expected Value (mm)	Mean Absolute Error (mm)	Mean Absolute Error (%)	Mean (mm)	Standard Deviation (mm)
Riser Height	Conventional	HFT1 L13	175	3	1.8%	173	3
Riser Height	MR	HFT1 L13	175	2	1.4%	176	3
Riser Height	Conventional	HFT1 B1	170	2	1.1%	169	3
Riser Height	MR	HFT1 B1	170	4	2.3%	173	4
Stair Width	Conventional	HFT1 L13	1015	5	0.5%	1015	7
Stair Width	MR	HFT1 L13	1015	81	7.9%	956	123
Stair Width	Conventional	HFT1 B1	1025	3	0.3%	1035	21
Stair Width	MR	HFT1 B1	1025	73	0.2%	1001	98
Stair Width	Conventional	HFT1 B1	1070	2	7.1%	1069	3
Stair Width	MR	HFT1 B1	1070	192	17.9%	1007	133
Headroom	Conventional	HFT1 B1	Varies	22	-	-	-
Headroom	MR	HFT1 B1	Varies	115	-	-	-
Headroom	Conventional	HFT1 L13	3470	69	2.0%	3467	81
Headroom	MR	HFT1 L13	3470	160	4.6%	3571	195
Headroom	Conventional	HFT1 L13	3600	14	0.4%	3598	21
Headroom	MR	HFT1 L13	3600	52	1.5%	3592	64
Headroom	Conventional	HFT1 B1	2090	4	0.2%	2087	5
Headroom	MR	HFT1 B1	2090	30	1.4%	2120	13
Headroom	Conventional	HFT1 L13	2690	6	0.2%	2692	9
Headroom	MR	HFT1 L13	2690	21	0.8%	2711	5

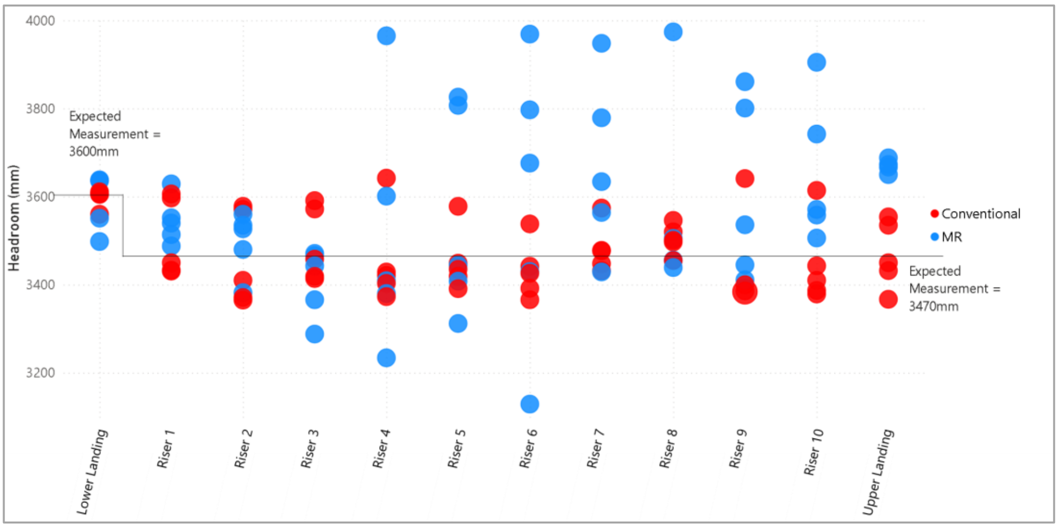


Figure 34. Headroom measurements at HFT1 L13 staircase

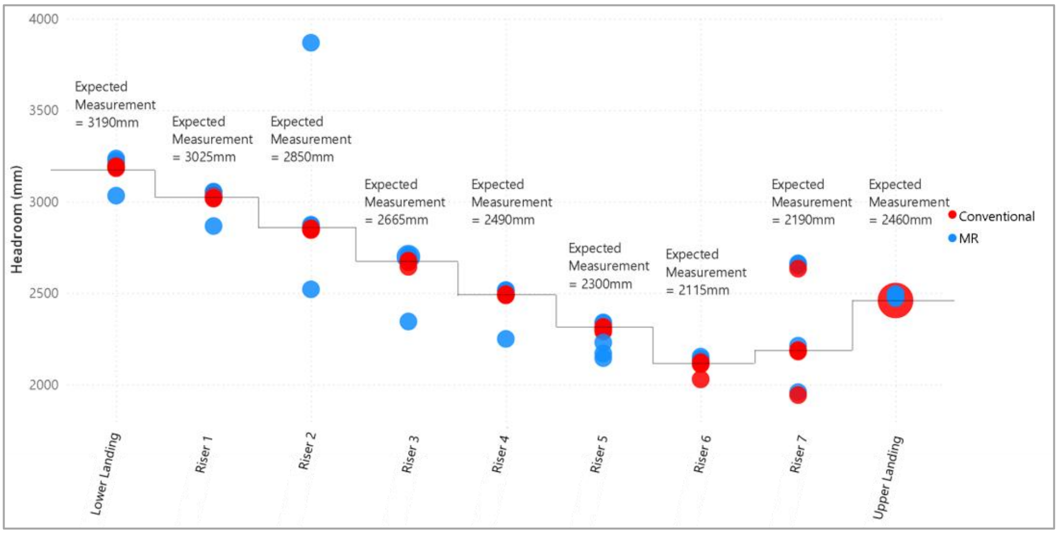


Figure 35. Headroom measurements at HFT1 B1 Staircase

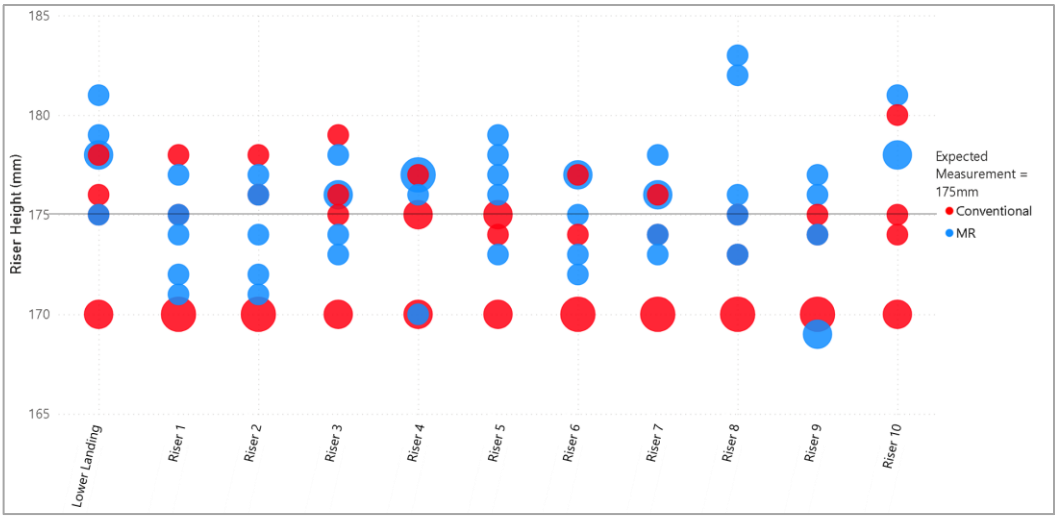


Figure 36. Riser height measurements at HFT1 L13 staircase

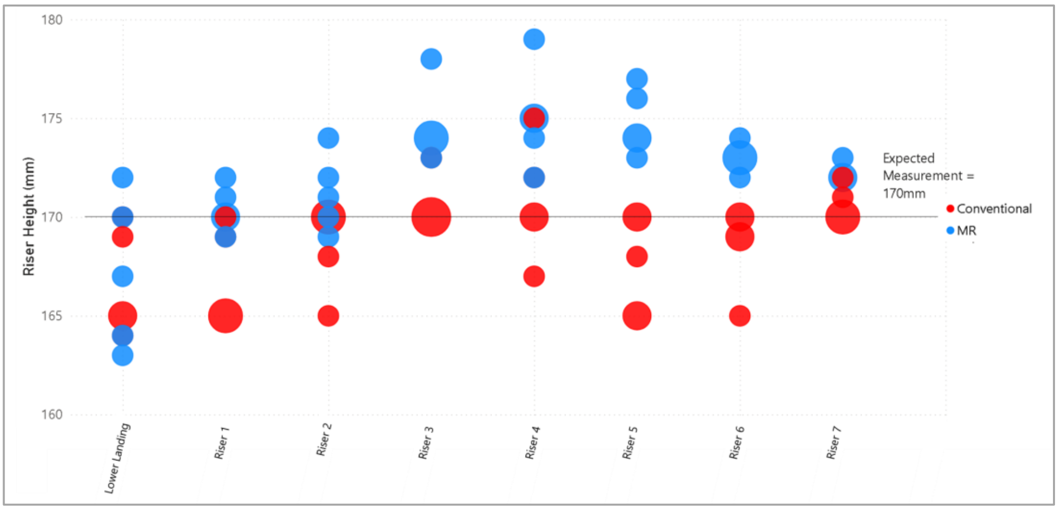


Figure 37. Riser height measurements at HFT1 B1 staircase

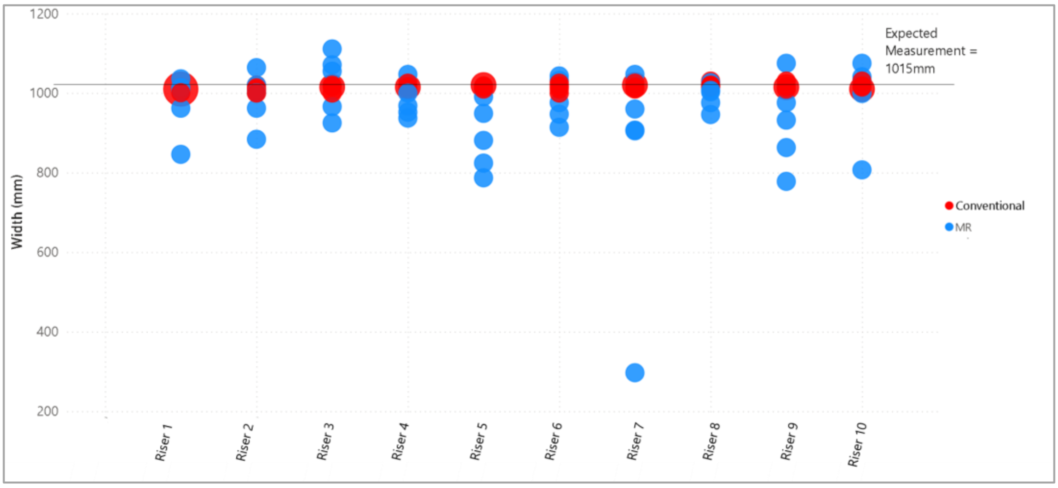


Figure 38. Staircase width measurements at HFT1 L13 staircase

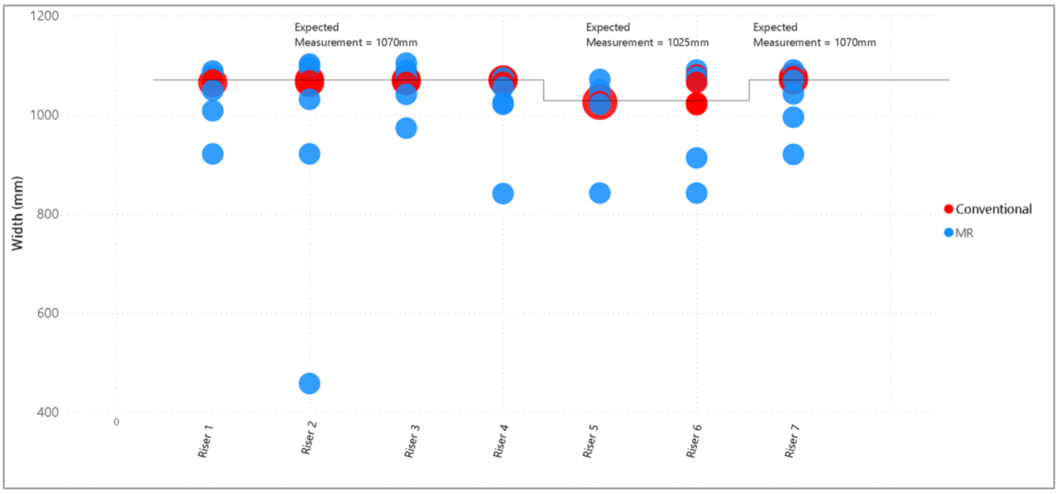


Figure 39. Staircase width measurements at HFT1 B1 staircase

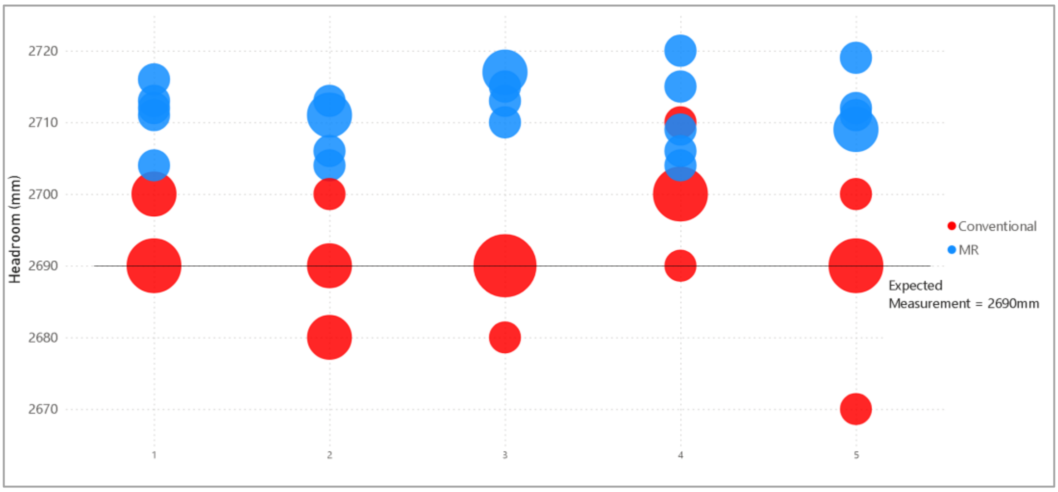


Figure 40. Headroom measurements at HFT1 L13 corridor

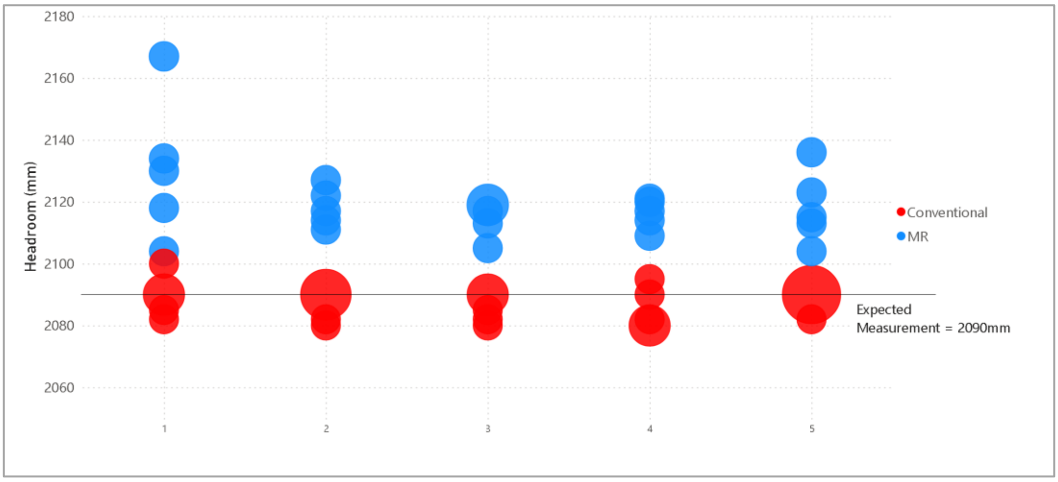


Figure 41. Headroom measurements at the HFT1 B1 corridor

Applying the scale factor from previous studies (Hübner, et al. 2019) effectively reduced the mean errors in the MR application's measurements for all categories except for staircase widths. The results with the applied scale factor are detailed in Table 17. Additionally, the observed scale factors, which varied slightly from the expected values, have been recorded for further analysis and comparison, which will be discussed in depth in Section 5.5.

Table 17. Summary of errors for scaled measurements and observed scale factors

Building Feature	**Tool**	**Location**	**Expected Value (mm)**	**Mean – Scale Factor = 0.988 (mm)**	**Mean Absolute Error – Scaled (mm)**	**Mean Absolute Error - Scaled (%)**	**Observed Scale Factor against Measured Values**	**Observed Scale Factor against Expected Values**
Riser Height	Conventional	HFT1 L13	175	-	-	-	-	-
Riser Height	MR	HFT1 L13	175	174	3	1.4%	0.9836	0.9963
Riser Height	Conventional	HFT1 B1	170	-	-	-	-	-
Riser Height	MR	HFT1 B1	170	171	3	1.7%	0.9751	0.925
Stair Width	Conventional	HFT1 L13	1015	-	-	-	-	-
Stair Width	MR	HFT1 L13	1015	945	85	8.4%	1.0576	1.0577
Stair Width	Conventional	HFT1 B1	1025	-	-	-	-	-
Stair Width	MR	HFT1 B1	1025	989	69	6.8%	1.0327	1.0230
Stair Width	Conventional	HFT1 B1	1070	-	-	-	-	-
Stair Width	MR	HFT1 B1	1070	995	204	18.9%	1.0583	1.0592
Headroom	Conventional	HFT1 B1	Varies	-	-	-	-	-
Headroom	MR	HFT1 B1	Varies	-	-	-	-	-
Headroom	Conventional	HFT1 L13	3470	-	-	-	-	-
Headroom	MR	HFT1 L13	3470	3528	150	4.3%	0.9699	0.9709
Headroom	Conventional	HFT1 L13	3600	-	-	-	-	-
Headroom	MR	HFT1 L13	3600	3549	51	1.4%	1.0016	1.0022
Headroom	Conventional	HFT1 B1	2090	-	-	-	-	-
Headroom	MR	HFT1 B1	2090	2094	8	0.4%	0.9844	0.9859
Headroom	Conventional	HFT1 L13	2690	-	-	-	-	-
Headroom	MR	HFT1 L13	2690	2679	11	0.4%	0.9926	0.9920

The functionality of the MR application to automate the dimensioning of staircase features was tested, with Figure 42 to Figure 44 showing the frequency of automated dimensions generated during the tests. Contrary to earlier tests at Osaka University, where automated headroom measurements were typically recorded at the initial risers, testing on the HFT L13 staircase at HarbourFront Tower One (HFT1) showed a distinct pattern: automated dimensions were more commonly generated for risers located farther from the start, particularly from the third riser onwards. In contrast, the HFT1 B1 staircase often failed to generate automated headroom dimensions, necessitating manual measurements. Similarly, the patterns for automatically generated riser heights and staircase widths primarily occurred further from the initialization point, typically starting from the fourth riser onward, aligning with the observations at Osaka University.

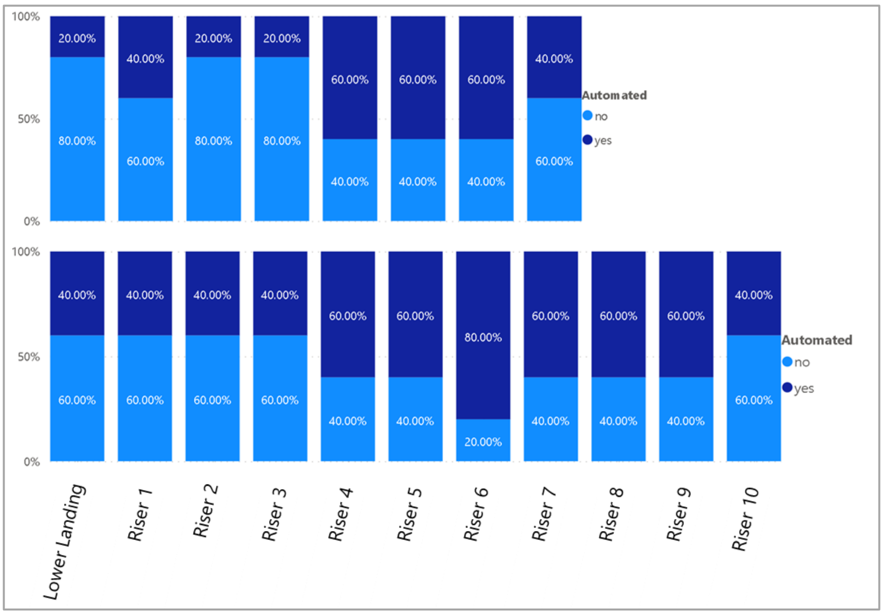


Figure 42. Occurrences of auto-generated dimensions – Riser height

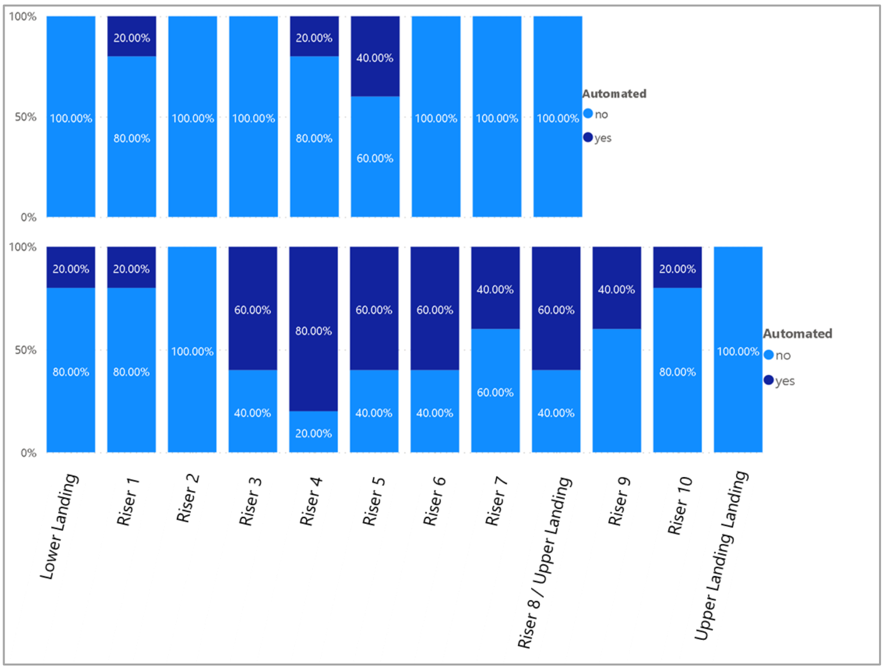


Figure 43. Occurrences of auto-generated dimensions - Headroom

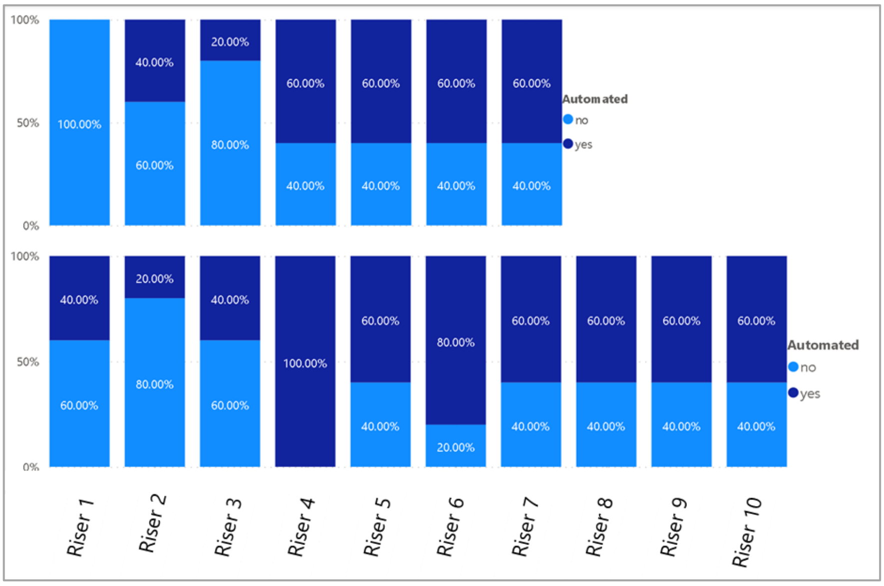


Figure 44. Occurrences of auto-generated dimensions - Staircase width

5.5.3 Results of opinion survey

The results of the opinion survey are presented in Figure 45. In general, the ease of use of the tape measure scored better than the HoloLens 2, but a majority did not answer an absolute no when surveyed on the perception of the accuracy of the HoloLens 2 results. This could be due to unfamiliarity with the technology behind how dimensions were computed in the virtual environment, but reported dimensions seem reasonable. Notably, some volunteers thought that the tape measure also did not provide accurate measurements, likely due to the subjectivity involved in reading off measurements. However, there were variable opinions regarding learning how to use the HoloLens 2. This suggests that while the technology is promising, there might be a potential barrier in terms of the learning curve. Further training and improvements in user-friendliness might need to be improved for enhanced usability in practical construction settings.

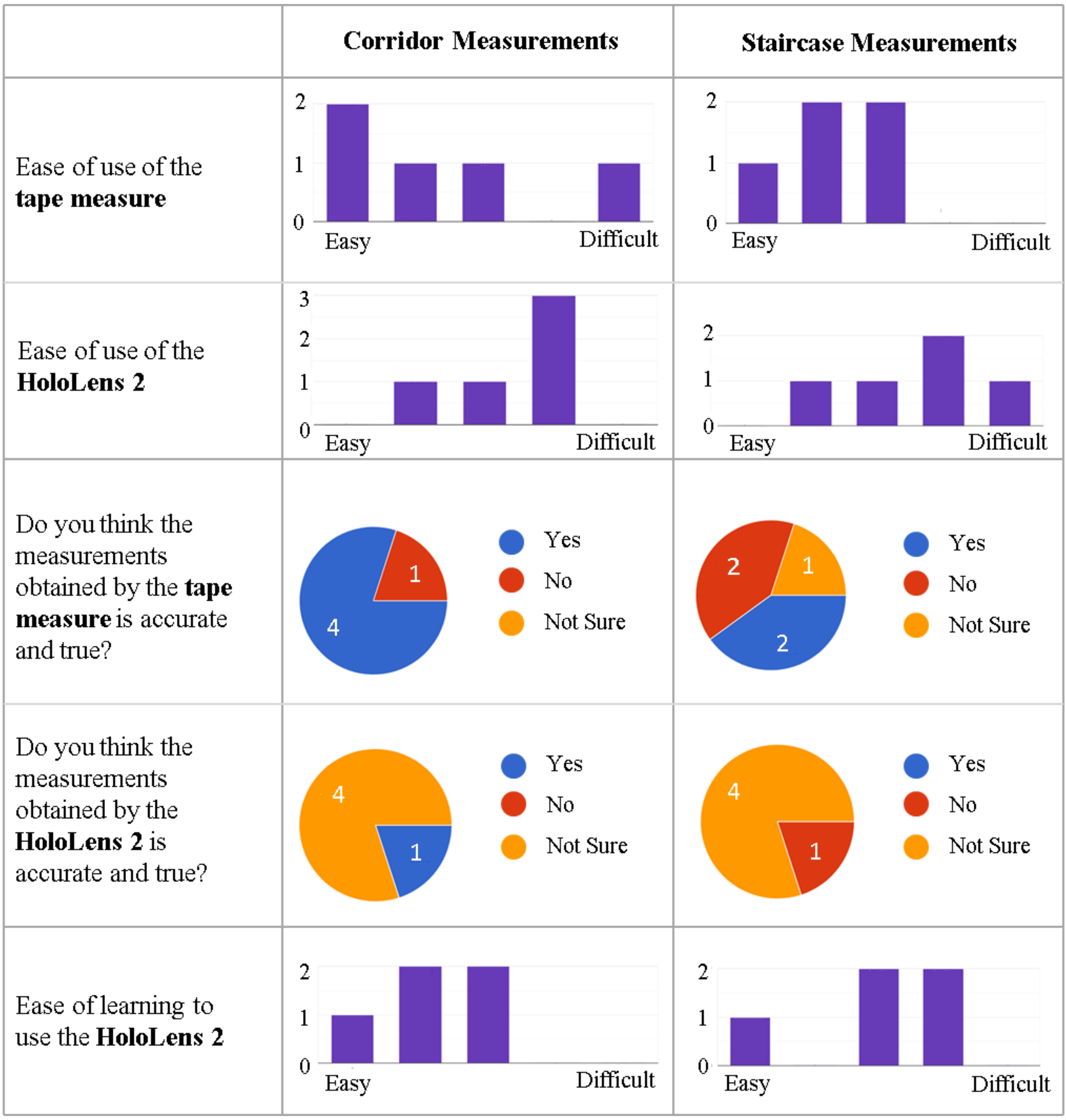


Figure 45. Results of opinion survey

5.6 Discussion

5.6.1 Variability and accuracy of measurements

5.6.1.1 Riser heights

The observed variability in measurements using conventional tools like tape measures and laser measures points to inconsistencies due to human factors despite using the same tools. Such variability could stem from actual differences in as-built structures or from the techniques different individuals use with these tools, reinforcing the fact that inconsistencies exist due to the heavy reliance on human factors (Prieto, Giakoumidis and de Soto 2021). The MR application, however, showed promise in reducing these inconsistencies; it exhibited standard deviations in riser height measurements comparable to those from conventional methods. Furthermore, applying a scale factor aligned the MR measurements more closely with expected values, demonstrating its viability as an efficient alternative for automatically obtaining precise dimensions. This potential reduces the reliance on manual measurement techniques, which are prone to human error, and offers a more standardized and reliable approach to capturing architectural dimensions.

In Singapore, reinforced concrete structures are typically allowed a construction tolerance of ±10 mm from the specified level (Building Construction Authority (Singapore) 2020). However, a more stringent regulation allows only a maximum tolerance of 5 mm between two consecutive steps and that riser heights must not exceed 175 mm (Building Construction Authority (Singapore) 2022). If the MR application were used for regulatory inspections, its observed standard deviation would comply with the former tolerance standard. However, any measurements above the 175 mm riser height would be flagged as non-compliant. Considering the regulatory requirements in other countries listed in Table 1, where riser height is often stipulated as a maximum, deploying the application specifically for such regulatory checks could pose challenges. Nonetheless, it is worth noting that the building where experiments were conducted was constructed in 2002 (Urban Redevlopment Authority (Singapore) n.d.), while the regulatory standards governing riser heights were not implemented until January 1, 2004 (Building Construction Authority (Singapore) 2022). This timeline discrepancy likely explains why many measurements exceeded the current maximum riser height requirement during experiments, even when traditional measurement tools were employed.

5.6.1.2 Headroom

Headroom measurements using the conventional method on the HFT1 L13 staircase showed up to 2% error, whereas the MR application displayed up to 5% error. The challenges of acquiring strictly vertical measurements on a sloping surface might account for the substantial errors seen in conventional measurements, as a slight tilt will lead to significant differences in the reported measurements. Additionally, MR headroom measurements at the HFT1 L13 Staircase approached the device's reported depth sensor range of 3.5 m to 4 m (Terrugi and Fassi 2022, Hübner, et al. 2020). The MR application, which uses computed meshes and a coordinate system to determine measurements, theoretically minimizes human error. However, its higher error margin and substantial standard deviation suggest difficulties in accurately generating meshes at certain distances, potentially affecting the reliability of measurements in scenarios with high headroom.

While measurements on sloping surfaces pose challenges, headroom assessments on flat surfaces are more accurate, exhibiting error margins of up to 1.5% and an absolute error of 52 mm. Applying a scale factor to the MR-computed measurements for corridor headroom that fall within the device's sensor range significantly improved accuracy, closely aligning with expected dimensions. Additionally, the standard deviations for these corridor height measurements were low, enhancing the promise of using MR technology for precise and reliable architectural assessments in suitable conditions.

Although previously reported scale factors of the HoloLens mesh ranged from 0.9879 to 0.9887 (Hübner, et al. 2019, Hübner, et al. 2020), which typically helped reduce measurement errors, the observed scale factors for riser height and headroom measurements in this study varied more widely, from 0.9699 to 1.0016. Notably, larger scale factors were often associated with headroom measurements near the device's sensor range limit, suggesting that distance from the sensor may impact the measurements' accuracy.

Considering many headroom regulations require a minimum of 2 meters, as detailed in Table 1, all test results would comply with these standards, even after accounting for the mean errors observed. This finding underscores the viability of using MR for headroom measurements on flat surfaces that are within the sensor's effective range of up to 3.5 meters, particularly when appropriate scale factors are applied. Therefore, MR technology demonstrates strong potential for ensuring compliance in regulatory contexts, particularly in straightforward, flat-surface scenarios.

5.6.1.3 Staircase width

The application measures staircase width by analysing the boundaries of generated quads, as outlined in Section 5.2.2. While staircase width definitions can vary due to factors such as handrail sizes and railing designs or other protrusions into the stairway space (Building Construction Authority (Singapore) 2022, Singapore Civil Defense Force 2018), for this proof of concept, stair width is defined strictly as the horizontal distance across each tread.

Among the different staircase features assessed, MR-computed staircase widths showed the highest errors and variances, primarily due to poor mesh generation, affecting the accuracy of mesh boundaries crucial for width calculations. Figure 46 exemplifies this with poorly generated mesh depicted by virtual objects, highlighting visible gaps noted in all tests conducted. These gaps consistently led to underestimating the actual staircase width, rendering these measurements unreliable at this stage. Therefore, enhancing mesh generation techniques or exploring alternative methods for measuring staircase width is essential. Further details on mesh generation and its challenges are discussed in the following section.

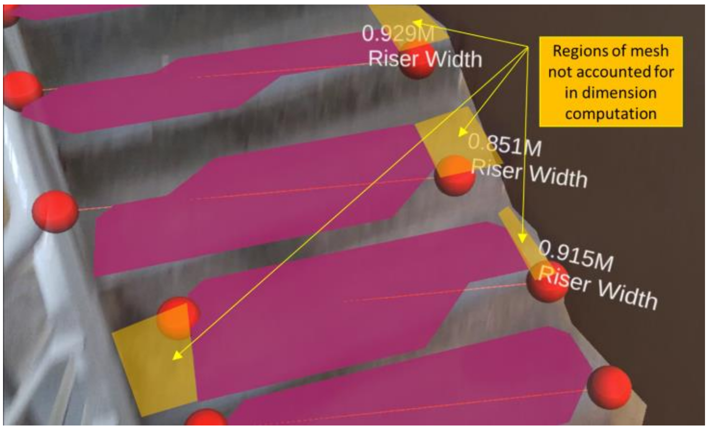


Figure 46. Staircase tread mesh visualisation

5.6.2 Feasibility of automating measurements using meshes

This study utilized automatically labelled meshes generated by the Scene Understanding SDK to compute measurements of staircase features using mesh coordinates. This section examines issues related to mesh generation and labelling observed during the tests.

The spatial map generated by the HoloLens during tests exhibited several anomalies similar to those observed in cathedral studies by Terrugi and Fassi (2022), including anomalies such as hallucinations, wormholes and bias. The following scenarios that resulted in a distorted spatial map are as follows:

- Changes in the environment during scanning, such as people moving through or doors opening into the scanned space, as shown in Figure 47, significantly impacted the HoloLens 2's ability to regenerate the spatial mesh within a reasonable time. The device took considerable time to adjust and accurately reflect the modified space. Further research is necessary to precisely quantify the time required for the mesh to stabilize and reliably represent the environment after such disruptions. This understanding will be crucial for optimizing the use of MR technology in dynamic real-world settings.
- Gaps too narrow for accurate detection by the spatial map were occasionally misinterpreted as solid surfaces by the HoloLens 2. This issue was particularly noticeable at the left edge of the HFT1 L13 stairs, where a small void exists between the lowest horizontal rail and the staircase tread, as illustrated in Figure 48. Such inaccuracies highlight the limitations of the HoloLens 2 in recognizing and differentiating between very close spatial features.

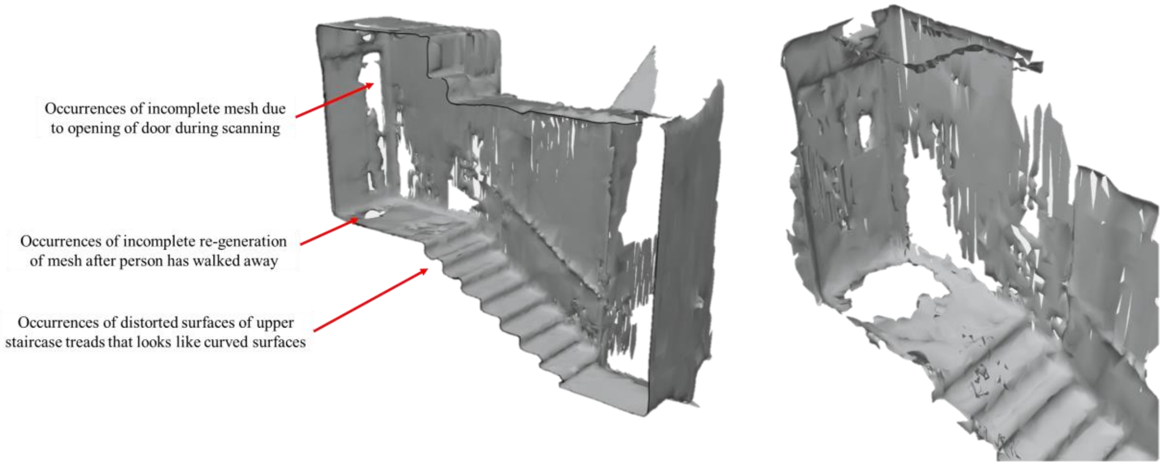


Figure 47. Mesh errors due to changes in the environment during scanning – separate occurrences during tests

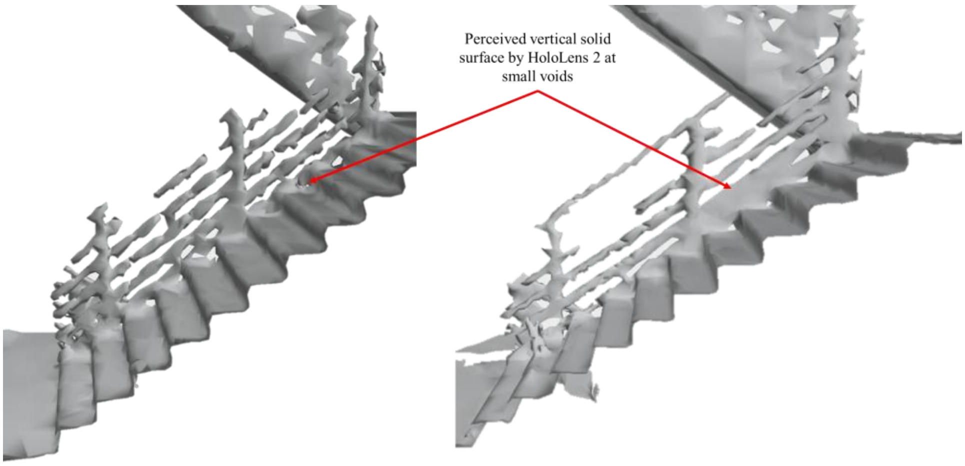


Figure 48. Hallucinated spatial surfaces in the spatial map

Figure 49 depicts a sectional mesh view of the staircase and corridor, revealing rounded edges at corners where 90-degree angles are expected. This visualization underscores inaccuracies in MR-derived staircase widths, which often appeared shorter than actual measurements due to the Scene Understanding SDK's interpretation of surface edges. The SDK seems to recognize the start of a curve as the edge rather than the actual intersection point of vertical and horizontal surfaces. Consequently, while riser heights and headroom measurements were accurately rendered, staircase width calculations were unreliable compared to the current methodology. Exploring alternative approaches, such as utilizing raw sensor data for semantic segmentation and feature extraction as suggested by Weinmann et al. (2020), might improve accuracy in future implementations.

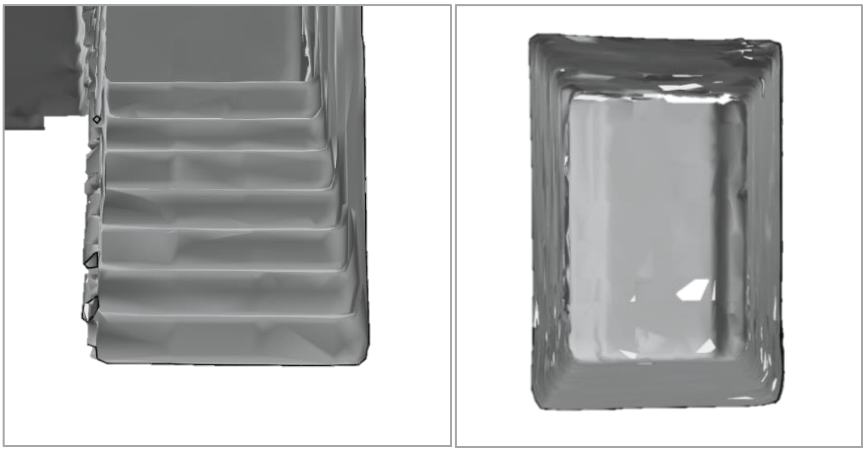


Figure 49. Sectioned mesh exported from HoloLens 2 – Staircase mesh (Left), Corridor mesh (Right)

5.6.3 Limitations

5.6.3.1 Experimental limitations

This study's small sample size of five industry practitioners, while limited, is mitigated by the breadth of data collected. Each participant used the MR application to measure dimensions at four distinct locations, resulting in 20 unique measurement scenarios. This diversity in measurement environments provides a comprehensive overview of the MR application's performance and reveals how spatial map accuracy varies by location and user. These findings highlight the need for further research to determine optimal environmental conditions that minimize errors, enhancing MR technology's reliability across various settings. The detailed implications of these variations and strategies for improvement are further discussed in Section 5.6.3.2.

Notably, the experimental design and MR system employed mimicked traditional measurement techniques, involving single point-to-point assessments that reflect real-world measurement practices. However, due to construction tolerances, individual points along building features may vary slightly, which the current methodology could not statistically resolve. This limitation highlights the inherent variability in building structures and underscores the need for comprehensive research into what constitutes acceptable accuracy within these contexts.

Additionally, while the application design was intuitively aligned to mimic conventional measurement methods, this study principally examined the technical feasibility and accuracy of the MR application's automated dimension acquisition and compliance checks. A comprehensive analysis of the application's user-friendliness and intuitiveness was not within the scope of this study. However, the ease with which volunteers could use the application effectively after just a brief tutorial suggests its intuitive design. Future research will expand to include detailed evaluations of these user experience aspects alongside the technical functionalities.

5.6.3.2 Technical limitations

Unexplained holes and distortion in some spatial maps were observed, as shown in Figure 50 and Figure 51, may stem significantly from the type of lighting within the test environments. A notable issue with the HoloLens is its interaction with 50 Hz fluorescent lighting—a common frequency in Europe, which mismatches the HoloLens's 60 Hz frame capture rate (Microsoft 2022). This mismatch likely causes frames to capture during the non-illumination periods of the light's flicker, leading to inaccuracies in mesh generation. This was particularly pertinent in tests conducted in Singapore, where the standard electrical frequency is also 50 Hz (National Environmental Agency (Singapore) 2023). Further studies are necessary to detail when and how such lighting conditions affect MR accuracy, as these lighting-induced distortions appeared randomly throughout the tests.

The experiments conducted at Osaka University highlighted the influence of semi-bright sunlight, as depicted in Figure 21, may have contributed to the gaps in the generated mesh. This observation underscores that various lighting conditions—whether artificial or natural sunlight—can significantly affect the quality of the spatial maps produced by the HoloLens. Lighting's impact is critical as it directly influences the device's ability to render and map the physical environment accurately, suggesting that optimal lighting conditions are essential for the reliable use of MR technology.

In addition to environmental factors, the application's data export and storage functionalities present technical limitations. The current method of documenting results through screen recordings and exported .txt files provides a visual record but is insufficient for detailed, real-world documentation needs. Future versions of the application could enhance utility by allowing exports of detailed dimensions for each staircase feature, facilitating deeper analysis and more robust verification of as-built models. Furthermore, a database architecture needs to be integrated with the current application so that such records can be stored systematically, where data can eventually be used with other systems such as the WBPMS progress monitoring framework. Addressing these data management challenges will enhance the application's practicality in various construction and inspection scenarios, alongside improving environmental factor resilience.

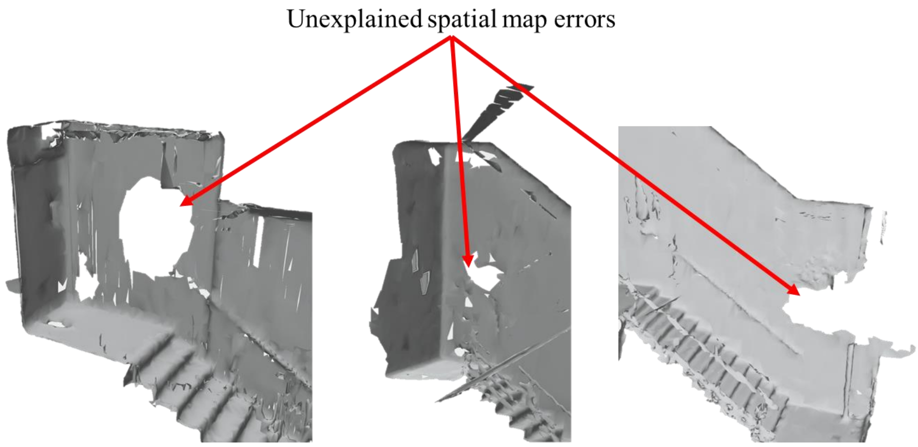


Figure 50. Cases of unexplained spatial map errors observed in staircases – HFT1 B1 (Left), HFT1 L13 (Center), Osaka U (Right)

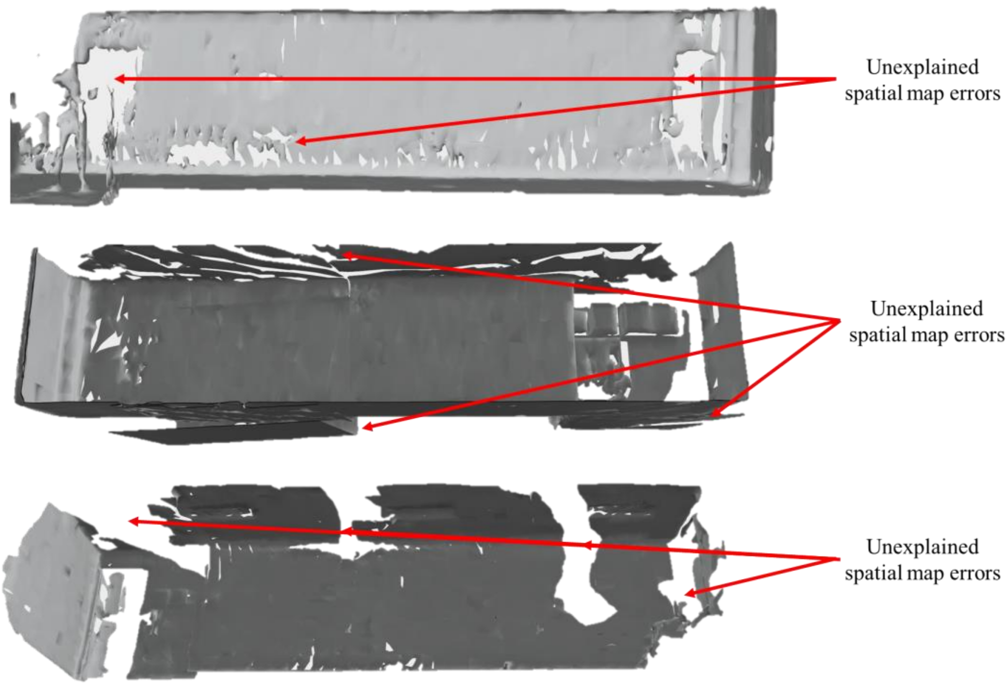


Figure 51. Cases of unexplained spatial map errors in Corridors - HFT1 B1 (Top), HFT B1 (Center), HFT L13 (Bottom)

5.6.3.3 Hardware limitations

The HoloLens was observed to have a battery life of close to 2 hours, shorter than the reported 2 to 3 hours, likely due to the high computational demands of processing meshes for automated dimensioning. Additionally, the device tended to overheat after about 1.5 hours of continuous use in mechanically ventilated spaces, with each test session lasting approximately 30 minutes. This overheating issue necessitates cooling periods, which could hinder practical application, particularly in construction sites without optimal ventilation. To mitigate such issues, implementing cloud processing could be explored as an alternative to on-device processing, where internet connectivity is available, to enhance efficiency and manage device overheating.

Employing a combination of a tablet and Head-Mounted Display (HMD) could potentially resolve the overheating issue observed with the HoloLens, as previously explored (Embers, et al. 2022). This approach would utilize the tablet's superior computational abilities for processing while the HMD would handle data collection and visualization. Although this setup might complicate the process solely for automating dimensional checks, it also offers a promising data management solution. Further investigations are essential to fully assess the practicality and benefits of this hybrid approach in real-world settings.

5.7 Summary

This study introduced a proof of concept for an MR-based dimensional inspection system designed to automate the comparison of measured dimensions against regulatory standards and identify on-compliances. The measurements obtained through the MR system were evaluated alongside those taken with conventional construction tools, highlighting the potential and limitations of this technology for practical applications. The findings suggest a promising future for MR in construction inspections, although further research is necessary to address the observed limitations and optimize the system's accuracy and reliability.

The MR application effectively measured plane-to-plane features such as riser heights and corridor ceiling heights within the device's optimal sensor range of 3.5 m to 4 m, with mean absolute errors between 0.4% and 1.7%. However, measurements along the sloping soffit of the staircase, close to the sensor's range limit, showed errors up to 4.3%. While plane-to-plane measurement proved successful, it failed to accurately determine horizontal measurements that required edge-to-edge measurements, such as staircase widths. This is due to the limitations of the HoloLens in generating the spatial map, which tends to form curves at edges, complicating the identification of endpoints necessary for accurate measurements.

The study demonstrated a method for automated dimensional checks using the Microsoft Scene Understanding SDK's semantic segmentation capabilities. The system could automatically compare dimensions against regulatory standards by segmenting spatial maps into labelled meshes to facilitate compliance checks. However, the findings indicated that automation is not fully reliable, with limitations in the SDK's ability to recognize and accurately label all necessary features for measurement consistently. At the point of this research, there are inherent limitations in the scene understanding SDK functionality.

The experiments highlighted how environmental factors like lighting and space changes impact the quality of spatial maps created by the HoloLens 2, necessitating further studies to determine optimal conditions for consistent application. The study also uncovered a scale factor in the spatial map generated by the HoloLens 2, consistent with past research (Hübner, et al. 2019, Hübner, et al. 2020). However, considerable variability was noted in meshes that were generated close to the device sensor's limits. Despite these insights, the small sample size and observed variability suggest that extensive testing is needed to uncover more definitive patterns and fully ascertain the MR technology's capabilities and limitations in practical scenarios.

During the experiments, limited battery life and overheating issues emerged as significant challenges, primarily due to the extensive computation required onboard the HoloLens 2. A viable solution to alleviate these concerns involves offloading the computational tasks to cloud services or utilizing a companion tablet. This approach would ease the device's processing burden and enhance functionality by enabling real-time updates and integration with various regulatory standards through cloud connectivity. Such adjustments could significantly improve the application's performance and reliability in practical settings.

In conclusion, while the HoloLens is not primarily designed as a scanning tool, its spatial mapping capabilities make it useful for plane-to-plane measurements like floor-to-ceiling distances within its 3.5 m sensor range. However, it does not achieve millimeter accuracy. Due to the limitations in the spatial map's accuracy, especially with edge-to-edge measurements such as staircase widths, the current system logic does not yield precise results for these types of measurements.

Therefore, future work will focus on refining the processing of spatial maps to accurately achieve edge-to-edge measurements, which is crucial for comprehensive virtual measurement applications. This involves enhancing spatial map segmentation and accuracy, particularly in handling environmental factors that affect map generation. Additionally, integrating these advancements into a database architecture will allow for the seamless incorporation of inspection results into the WBPMS framework, facilitating real-time progress monitoring on top of compliance verification. This integration promises to streamline the workflow and utilize the status results generated from MR-based inspections to infer and update the project's progress automatically, enhancing the overall efficiency and reliability of the construction management process.

Chapter 6
Conclusion

6.1 Summary

This dissertation aims to enhance construction progress reporting by developing a framework that addresses the practical needs of professionals in the field. This study investigates general contractors' specific progress reporting requirements and leverages inherent data from construction processes, thus eliminating the dependency on complex technologies for reporting. While the proposed WBPMS framework simplifies technology use, it also explores how advancements, particularly in Mixed Reality (MR), could automate inspections and integrate these results to infer project progress accurately. This approach streamlines the monitoring process and aligns with technological advancements to improve efficiency and accuracy in construction project management.

In summary, the WBPMS framework utilizes SystemsDB and WorkflowDB to integrate domain expert knowledge and automate the linkage of construction databases with BIM to deduce project progress from document statuses. This system avoids the need to create additional documents, unlike other automated solutions that require deploying new technologies. Updates to statuses in BIM are made in real-time as construction processes occur, allowing for the immediate extraction of visual progress reports directly from BIM and eliminating manual data consolidation. The WBPMS was successfully applied to a piling activity, producing progress reports that reflect actual documentation accurately.

This study also explored automating quality inspection processes using MR, specifically employing the HoloLens 2, which utilizes semantic segmentation of meshes and mesh coordinates to measure dimensions. Automated compliance checks are performed using if-then rules to assess these measurements against regulatory standards. Despite showing promise for room-scale measurements such as ceiling heights, the accuracy is constrained by the quality of mesh generation from the depth sensors, highlighting the need for technological enhancements to improve the reliability of MR applications in construction inspections. Integrating the results of such inspections into the WBPMS will require further studies, particularly focusing on developing database storage solutions for inspection results to realize the full potential of automated digital inspections. This research phase primarily demonstrated the feasibility of such technological applications in real-world scenarios.

The chapter provides a comprehensive discussion of the research contributions, limitations, and future work directions. This analysis encapsulates the insights gained from implementing the WBPMS framework and the MR methodology for automated dimensional checks in construction processes. It also critically evaluates the potential impacts and limitations of the current technologies used and outlines prospective improvements and areas for further investigation that could enhance the efficacy and accuracy of construction progress monitoring.

6.2 Research contributions

The main research contributions to develop the framework, as well as the MR solution for automated inspection, are as follows:

(1) Development of a framework for semantic enrichment of BIM for automating progress reporting: The framework developed in this study leverages actual project data from progress reports, claims, and schedules to identify critical information requirements. Following data analysis, a SystemsDB and a WorkflowDB were established: the former stores configurations on the relationship of workflow types to construction elements and the latter manages workflow sequences for project stages. Substages in construction are quantified through document statuses such as approvals and inspections, synchronized into BIM to reflect real-time progress. This method uses Dynamo scripts to efficiently link construction process statuses with BIM elements, enhancing report preparation with reduced latency and increased accuracy compared to traditional methods that rely on post-processed data from advanced instruments like laser scanners. Unlike previous studies, this approach utilizes existing data from standard construction processes, thus avoiding the deployment of additional hardware.

(2) Scene understanding for Dimensional Compliance Checks in Mixed-Reality: To enhance efficiency in construction quality inspections, an MR application using the HoloLens 2 was developed to automate dimensional checks, utilizing sensor data to compute as-built measurements on the spot. This application can verify measurements against regulatory requirements without relying on BIM models for comparison, marking a significant departure from previous methodologies. Key distinctions of this research include: (1) pioneering the use of MR device sensor data for dimensional regulatory inspection; (2) eliminating the need for BIM-based comparisons, relying solely on sensor data. Despite its measurement accuracy limitations, this approach presents a novel and streamlined method for conducting automated inspections.

6.3 Limitations and future research

While the proposed framework significantly enhances efficiency in construction progress reporting, it also presents certain limitations that necessitate further research. This section will discuss these challenges in detail and explore potential avenues for future studies to refine and optimize the methodology. Addressing these limitations is crucial for advancing the framework's applicability and reliability in real-world settings, ensuring it can effectively meet the evolving needs of construction professionals.

The proposed framework for semantic enrichment of BIM leverages a construction information database, which depends on real-time updates from construction processes through systems or manual register updates. Such real-time data updates can be compromised in environments with poor connectivity or through delayed manual entries, impacting the timeliness and reliability of progress reporting. Additionally, digital systems may have database architectures that are incompatible with the data standards or formats required by the WBPMS. Not all digital systems possess complete database structures, as illustrated by the Hubble System's missing information on exported databases. To facilitate seamless integration, developing APIs to connect with various systems is necessary; however, this is contingent upon the technology providers' API policies and potential costs per API call. Despite these challenges, this study successfully demonstrated a method to integrate data effectively to reproduce construction progress reports.

While the WBPMS is designed to minimize the need for extensive user training, its adoption still requires at least one expert user familiar with the SystemsDB, WorkflowDB structures, and the use of BIM. The system's reliance on keyword searches to navigate construction databases for progress mapping introduces some inflexibility, particularly with potential typographical errors in data entries. This limitation suggests a potential area for further research, such as integrating Large Language Models (LLMs) to enhance the robustness and accuracy of the search functionality within the framework.

While promising, the MR technology for automated dimensional checks encounters several limitations that may impact its commercial viability. Key issues include the insufficient accuracy of current mesh generation techniques for horizontal measurements and the influence of environmental factors, such as lighting and obstructions, which degrade measurement precision. Additionally, the limited two-hour battery life and overheating concerns pose practical challenges in field applications. There might also be regulatory hurdles, as automated inspections may not yet be recognized as equivalent to manual methods by authorities, necessitating updates to existing regulatory frameworks. Importantly, for integration with the WBPMS, results from MR inspections need to be systematically captured into a database, ensuring seamless connectivity and data utilization within the broader project management framework. This integration is critical for leveraging real-time data to enhance construction progress monitoring and reporting. Further research is needed to address these technical and regulatory challenges to realize the full potential of MR in construction inspections.

Lastly, to fully realize the potential of the WBPMS and the MR application, further validation through more case studies in actual construction environments is essential. This will help refine the technologies based on real-world feedback and performance and demonstrate their practical viability and effectiveness in live scenarios. It is crucial to conduct these case studies across diverse settings to comprehensively understand the strengths and limitations of the systems under various operational conditions. Such studies will be instrumental in making the necessary adjustments to optimize the technologies, thereby enhancing their reliability, accuracy, and user-friendliness in routine construction progress monitoring. This iterative process of testing and refinement will ensure that the solutions developed are robust and can significantly contribute to the construction industry's digital transformation.

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