From physical site to digital insight

Real-time site data and digital twins for project management in the construction execution phase

Master's thesis in Design and Construction Project Management

IVAR APPELGREN
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Abstract

The construction industry is characterized by complexity and fragmented information flows. At the same time, the sector continues to face challenges related to delays, cost overruns, and safety risks during the execution phase. This study aims to evaluate the potential of vision-based Digital Twin (DT) concepts and visual site documentation as support tools for project management in the construction industry. Particular attention has been given to practical applicability and the user perspective. As such, the study is relevant for construction professionals, project managers, site managers, technology providers, and researchers interested in how digital tools can support more proactive and data-informed management practices.

This study follows a qualitative research design, combining a literature review with empirical data from exploration of Dalux SiteWalk, interviews and a workshop with construction professionals, and practical testing of AI-supported safety risk detection using 360° site imagery. The theoretical foundation builds on a combination of construction project management theory, vision-based site documentation and DT concepts, DT maturity levels, AI, and Computer Vision (CV).

The findings show that vision-based DTs currently create value mainly through passive documentation, visualization, traceability, remote site access, and improved situational awareness. However, their potential extends further, for example, in relation to progress monitoring, deviation detection, cost and schedule control, quality assurance, and safety management, particularly when combined with AI and CV. At the same time, the study identifies limitations related to both technical and organizational maturity, workflow integration, data quality, user adoption, surveillance concerns, and the need for human validation of AI-generated outputs.

The study concludes that vision-based DTs should not be understood as a ready-made autonomous solution, but as a gradually maturing tool that can evolve from visual documentation into decision-support systems, following a conceptual five-step framework. The framework illustrates the development path through which construction organizations can build value progressively through lower and higher levels of DT maturity.

Keywords: Vision-based digital twins, 360°-imagery, visual site data, construction project management, construction execution phase, AI, computer vision

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Ivar Appelgren, Gothenburg, June 2026
Jonas Störsrud Erixon, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
BIM	Building Information Modelling
CV	Computer Vision
DT	Digital Twin
LiDAR	Light Detection and Ranging

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1
Introduction

This chapter introduces the focus of the study and outlines the reasons why it is crucial and valuable to investigate. It also provides background, presents the aim of the study, outlines its delimitations, and introduces the research questions.

1.1 Background

The construction industry plays a central role in shaping our society by driving economic development as well as providing and maintaining essential infrastructure that society demand on every day (McKinsey Global Institute, 2017). In Sweden, the sector is an important backbone of the economy, accounting for between 10 and 11.5% of Sweden's GDP over the past decade (Byggföretagen, 2026). The construction sector also creates employment opportunities for people with various educational backgrounds and employs between 350.000 and 400.000 people in Sweden (Statistiska centralbyrån, 2024; Byggföretagen, 2024). However, despite the industry's scale and importance for society, it is often perceived as lagging behind other sectors, such as manufacturing, particularly when it comes to productivity and how digitalized it is (McKinsey Global Institute, 2017; Omrany et al., 2023).

On the other hand, construction projects are known for being complex, where projects, as a standard basis, involve multiple stakeholders, heterogeneous resources, temporary project teams, and dynamic interactions (McKinsey Global Institute, 2017). This complexity can be difficult to manage alone, but it gets even more difficult when it needs to be done within tight timeframes while ensuring projects stay within budget and maintain high quality. These conditions indicate that efficient project management is needed, where it is critical to make decisions based on reliable and up-to-date information (Project Management Institute, 2021; Radman et al., 2025). Taken together, these conditions amplify the need for innovative technologies and data-driven approaches that can help advance the industry's efficiency, sustainability, and performance across projects.

Furthermore, the construction industry has been known for its repetitive and well-documented challenges related to cost overruns, delays, and working environment and safety concerns (Samuelsson, 2025; Abdelalim et al., 2025). Research shows that these problems often stem from insufficient real-time information, disconnected information flows, and manual periodic follow-up procedures in project management practices (Radman et al., 2025; Sacks et al., 2020). Without continuous and reliable progress tracking, it is also difficult to detect deviations early, thus limiting the possibility of acting proactively and taking action before problems escalate into delays, cost overruns, or accidents.

To address these challenges, the construction industry has begun implementing digital tools as a part of a broader digitization development and transition towards an Industry 4.0 approach (El Jazzar et al., 2020; Oesterreich & Teuteberg, 2016; Radman et al., 2025; Sacks et al., 2020). Some examples of these technologies and tools are Building Information Modeling (BIM), sensor systems, and data analytics, which have helped improve visualization, coordination, and information sharing between project stakeholders (Oesterreich & Teuteberg, 2016; Sacks et al., 2018; Tighnavard Balasbaneh & Sher, 2026). Despite this, these tools are often used in isolation from each other and in many cases rely on manual updates (Oesterreich & Teuteberg, 2016; Radman et al., 2025). This fragmentation of data and lack of integration limit their ability to provide continuous and real-time support for decision-making in the execution phase (Radman et al., 2025).

Given this background and problem context, the concept of DTs has recently gained increased interest as a promising tool to improve transparency, provide real-time decision-making support, and governance in the construction industry. DTs are generally explained as dynamic and digital representations of physical assets or processes where data from reality is integrated into a digital model to enable analysis, simulations, and predictions over the construction project lifecycle (Yang et al, 2024). Thus, DTs share similarities with regular BIM models, but as a real-time representation of what is built, rather than what is planned to be built. Currently, DTs are mostly used for facility management and building operating purposes, with Vasakronan serving as an example of industry adoption (Sweco, 2025; Twinfinity, n.d.; Vasakronan, 2025). However, research shows that DTs also have the potential to improve project management by supporting time planning, cost and progress tracking, and risk management, particularly when combined with 4D-and 5D-BIM (Sacks, 2020; Reja et al., 2024).

In combination with AI, there is thus further development potential for simpler digital representations to practical project management decision support in the construction phase. According to Pal et al. (2023) and Reja et al. (2024), several studies suggest that automated analysis of visual data can be applied to support safety and risk assessment at construction sites, identify errors, and monitor the status of production. By integrating image- and vision-based site data into the DT, the project manager's duties can be streamlined and, in some cases, automated without requiring resource-intensive methods like laser scanning (Pal et al., 2023; Yang et al., 2024). This also highlights an alternative perspective on DT concepts. Rather than prioritizing maximal geometric precision, the focus shifts to usability, update frequency, and economic viability (Reja et al., 2024; Yang et al., 2024). This shows the importance of developing DT solutions that are both practically useful and align with the actual needs of construction professionals.

However, despite these developments, there is still limited understanding and practical experience of how DTs and visual site data can be effectively applied to support project and site management during the construction execution phase. Existing research focuses mainly on technical and theoretical opportunities, conceptual frameworks, and applications for operation and facility management purposes. Meanwhile, less attention has been directed towards the user perspective and implementation in construction project execution (Reja et al., 2024; Yang et al., 2024). Furthermore, integrating AI tools to support project management processes is still in its early stages, and there is a lack of knowledge of how such solutions can help address industry challenges related to time, cost, and safety in practice.

1.2 Aim and objectives

This master's thesis aims to evaluate the potential of DT concepts and visual site documentation as support tools for project management in the construction execution phase, with a particular focus on the user perspective and practical applicability. Thus, the result of the thesis aims to provide a foundation for guiding the technology transition toward what is expected and desired in the industry, as well as how it can most efficiently help mitigate fundamental industry challenges in practice. In addition, the study aims to explore the potential of AI and CV to analyze visual site data and support, or potentially automate, project management practices.

Thus, a set of objectives was formulated to guide the path for the study:

- Examine how digital visualization tools are currently used by project management professionals on construction sites.
- Examine how these tools influence project management practices related to time, cost, and safety.
- Identify challenges and limitations for further implementation and use of vision-based DT concepts in construction projects.
- Explore how these tools can be further developed combined with AI and CV technologies to better support project management practices.

1.3 Specification of research questions

Given the background and the problem formulation, this study aims to address the research question:

How can vision-based digital twin solutions evolve from visual documentation tools into decision-support systems to enable more proactive project management during the construction execution phase?

1.4 Delimitations

This thesis seeks to explore the potential of vision-based DTs that rely on visual sensing technologies, such as 360°-imagery, rather than laser scanning and Light Detection and Ranging (LiDAR) techniques. In addition, the focus will be on the building construction sector from a project management perspective during the construction phase, which is still a relatively unexplored area.

The thesis primarily revolves around, but is not fully limited to, Peab's operations within the Swedish construction sector. The focus will be on leading roles during the construction phase, such as site managers, project managers, and site supervisors. The empirical results and insights gained during the process will mainly be based on interviews and discussions with representatives from Peab and their subcontractors, and will draw on projects within their project portfolio in which the concept of DTs or visual site data has been tested. Thus, user-perspective conclusions will be derived mostly based on insights from Peab employees and should therefore be interpreted as representative of a large-scale construction company operating in Sweden. The findings will, therefore, not necessarily be fully transferable or applicable to companies of different sizes or operating in different contexts. The work will be focused on the implications of DTs in the construction phase, since this stage is where progress measurement, safety rounds, and operational control are considered to be most relevant.

1.5 Sustainability

From a sustainability perspective, this study is contributing to sustainable development by addressing key challenges in the industry related to both economic and social sustainability dimensions. By exploring the potential of vision-based DTs as a support tool for project management practices, this study examines how such tools can improve resource efficiency, reduce waste, and improve cost and time control, thereby supporting economic sustainability.

Additionally, by investigating how managerial practices and workflows can be streamlined, potentially reducing workload and working conditions for managerial roles, the study can also be argued to contribute to social sustainability. The study also contributes to social sustainability by addressing challenges related to the on-site work environment and safety, communication, and easy access to information on construction sites.

Finally, this study focuses on the user perspective and practical applicability. The motivation for this direction is to highlight the necessity for technological tools to be accessible, usable, and to generate clear value to end users. Having this perspective in the center of mind is essential for achieving long-term sustainable impact in both social and economic contexts.

2
Background and Related Work

The literature review is structured like an inverted pyramid. It begins with a broad description of the challenges that the study aims to address. The chapter then gradually narrows down to project management during the construction execution phase and the tools, concepts, and technologies that may help address these challenges. Particular focus is given to digital-twin concepts, vision-based site documentation, AI, and CV.

2.1 Challenges in the construction industry

The construction industry is known for its high complexity, both in terms of project and organizational dimensions (Gomez-Cabrera et al., 2024; Lafhaj et al., 2024). Each project is unique and requires different competencies, leading to temporary project teams and new challenges to face. Although this can be seen as part of the industry's charm, this complexity comes with challenges. Three well-known challenges and recurring problems in the construction industry are delays, cost overruns, and poor safety conditions (Abdelalim et al., 2025; Gómez-Cabrera et al., 2024; Lafhaj et al., 2024; Purushothaman et al., 2024; Samuelsson, 2025; Smita & Bhole, 2016). The following two subsections further highlight these problems, including causes and contributing factors.

2.1.1 Safety issues and accidents on site

Safety management is an essential subject in an industry such as construction, characterized by operations involving risks and poor safety conditions, as reflected in work-related injury statistics (Lafhaj et al., 2024; Samuelsson, 2025; Smita & Bhole, 2016). Although the statistics show an improvement over the last three decades (Samuelsson, 2025), safety remains a recurring issue that needs to be addressed to ensure that everyone gets home safely from work every day.

In addition to these Swedish statistics, an additional study from the UK has been looked into to better understand the reasons behind the accidents. When summarizing the results from the study, three clearly dominant causes of injuries can be identified (Smita & Bhole, 2016), see Figure 2.1. These are injuries while handling, lifting or carrying; slips, trips, or falls on the same level; and falls from a height.

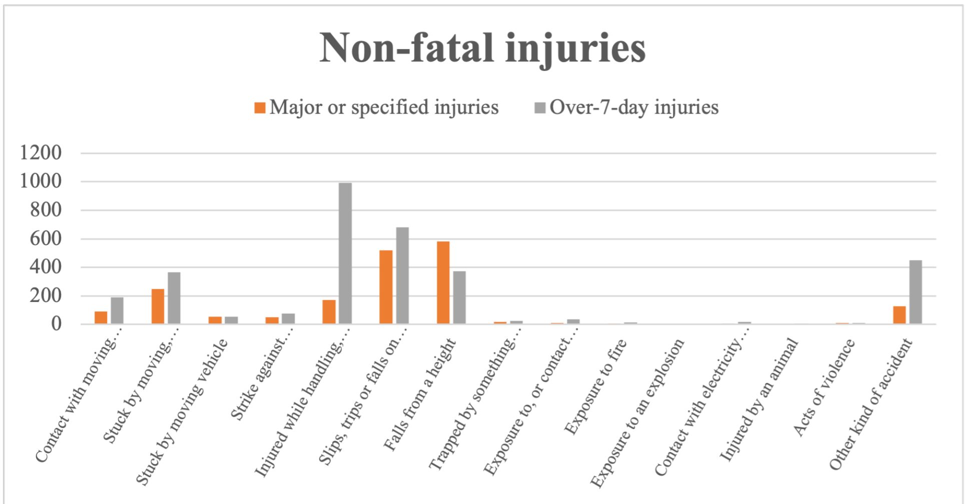

Figure 2.1: Causes of non-fatal injuries (Smita & Bhole, 2016).

Furthermore, if looking solely at fatal injuries, the numbers look different. While handling-, lifting- or carrying-related injuries and slips, trips and falls on the same level represent a big portion of the non-fatal injuries, these categories have no documented fatal outcomes. Meanwhile, falls from a height turned out to be the main cause of the fatal injuries, representing 39% of the fatal injuries in the construction sector in the UK during the year 2013-2014, see Figure 2.2 (Smita & Bhole, 2016).

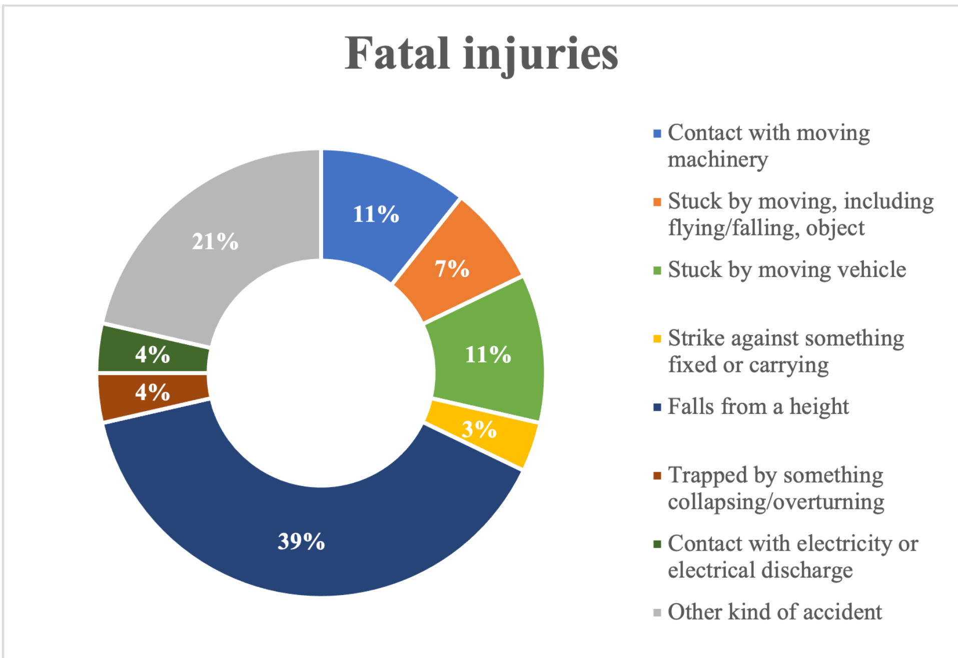

Figure 2.2: Causes of fatal injuries (Smita & Bhole, 2016).

Even though these statistics are gathered in the UK, and almost a decade ago, clear similarities can be found in recent updated information from the Swedish Work Environment Authority (Swedish Work Environment Authority, 2026). Here, three main causes of occupational accidents are identified, including falling to a lower level, falling on the same level, and losing control of a hand tool or machine. Meanwhile, falling to a lower level is identified as the main risk causing fatal accidents.

Taken together, the statistics suggest that isolated technical failures rarely cause construction accidents. Instead, they are largely the consequences of taking shortcuts in how work is planned, supervised, and executed. Smita & Bhole (2016) point out three fundamental root causes of why accidents occur: failure to recognize hazards, execution of work in unsafe conditions, and decisions to proceed despite awareness of unsafe conditions. Thus, both inherently unsafe site conditions and unsafe or nonchalant behavior of workers turn out to be two key factors that must be further addressed within safety management practices.

In line with this, Kinga Wasilkiewicz et al. (2024) demonstrate empirically that on-site safety performance is strongly connected to the overall project management quality. The authors therefore argue that safety management should be treated as an integral component of project management activities, rather than a separate and reactive function. The path forward, according to Kinga Wasilkiewicz et al. (2024), thus lies in proactive and systematic integration of safety considerations into project management, to avoid polarization between value creation and safety measures.

2.1.2 Delays and cost overruns

Briefly explained, the foundation of a successful construction project, both today and historically, is delivering high-quality technical performance within given budget and time constraints (Frimpong et al., 2003). However, although schedules and costs are cornerstones of how to measure success in the construction industry, time and cost performance are recurring challenges. Despite recent advancements in project management methods, digital tools, and contracting strategies, time and cost overrun remain major issues (Abdelalim et al., 2025; Gómez-Cabrera et al., 2024). Similar to safety issues, delays and cost overruns can rarely be explained by isolated problems. Instead, they are often the result of a combination of complexity, uncertainty, and interacting organizational and managerial factors that are embedded in project environments (Lafhaj et al., 2024; Purushothaman et al., 2024).

In a comprehensive review by Gómez-Cabrera et al. (2024), several dominant causes for time and cost overruns were identified. These include poor site management and financial control at the site, poor planning and scheduling, delays in progress payments, and design changes or change orders. In addition, external factors such as a shortage of materials and market volatility are mentioned as contributing factors. Similarly, Abdelalim et al. (2025) argue that cost overruns globally are connected to inefficient project planning and management, unstable or unclear project scopes, contractor performance issues, and economic alterations. When cross-reading the findings from these studies, it is suggested that time and cost overruns share overlapping root causes, which shows an interdependency between schedule and budget performance (Abdelalim et al., 2025; Gómez-Cabrera et al., 2024).

Focusing on delays, Tafesse (2021) highlights a few critical factors that contribute to late deliveries. Among the most outstanding factors are a lack of planning and scheduling, inefficient site management, a shortage of resources such as labour, materials, or equipment, slow decision-making processes, and frequent design changes. Notably, these factors often occur during the execution phase, where coordination between stakeholders is most intensive. Tafesse (2021) also emphasizes that delays are rarely the result of single failures. Instead, they emerge from weakness in planning, communication, and supervision that build upon each other.

A valuable insight from recent literature is that various causes of delays may interact and trigger each other. Purushothaman et al. (2024) explain that typical delay drivers can interact in reinforcing ways. For example, facing incomplete or unclear design information can lead to unnecessary rework. This, in turn, risks increasing congestion on site, leading to reduced productivity and creating further scheduling pressure. Additionally, such a chain of reinforcing events may trigger acceleration measures or additional resource allocation, which increase costs. Furthermore, Lafhaj et al. (2024) argue that construction projects are naturally complex systems that are characterized by multiple interdependencies among, for example, stakeholders, technical components, human resources, and regulatory requirements. In such environments, even small disturbances and deviations risk spreading and amplifying throughout the system and escalating into significant time and cost consequences.

Taken together, the literature indicates that delays and cost overruns are largely the consequences of how projects are planned, coordinated, controlled, and executed. Thus, insufficient on-site monitoring, fragmented information flows, and delayed decision-making processes further amplify the effects of uncertainty and complexity that are embedded by nature (Gòmez-Cabrera et l., 2024; Purushothaman et al., 2024). Similar to how safety performance is closely connected to overall project management quality, time and cost performance also seem to be strongly dependent on efficient project management practices, particularly during the execution phase. This, in turn, connects with Lafhaj et al. (2024), who argue that complexity must be managed through systematic coordination and continuous updating of plans. Abdelalim et al. (2025) further point out the importance of strengthening forecasting, risk management, and cost control mechanisms to prevent cost overruns from escalating. Overall, the literature points toward the benefit of integrating proactive and data-informed project management approaches. Such an approach would help identify deviations early, understand interdependencies, and support corrective actions in time. Thus, the path forward not only lies in improving initial planning but also in improving real-time visibility and control during the project execution phase.

2.2 Project management in construction

The concept of project management can be seen as a framework with coherent activities and have the purpose of delivering value under uncertain circumstances. According to the PMBOK, project management is built around eight performance domains that are interdependent. A performance domain is a category of interrelated activities, and these eight domains lay the foundation to deliver a successful project. The following eight performance domains include areas such as stakeholder, team, development approach and life cycle, planning, project work, delivery, measurement and uncertainty. Among these, measurement and uncertainty performance domains are particularly important since they highlight the relevance of tracking the project status, data that can facilitate decision making, and maintaining alignment with project objectives versus actual performance.

In dynamic construction projects, effective measurement is essential for monitoring and managing the project. Further on, the uncertainty performance domain points out that every project is exposed to uncertainty, ambiguity, complexity, volatility, and risks. Managing projects effectively, it entails a continuous search for schedule and cost deviations, safety risks, and lack of performance. Thus, these domains emphasize how crucial structuring the information and giving feedback continuously is in functional project management (Project Management Institute, 2021).

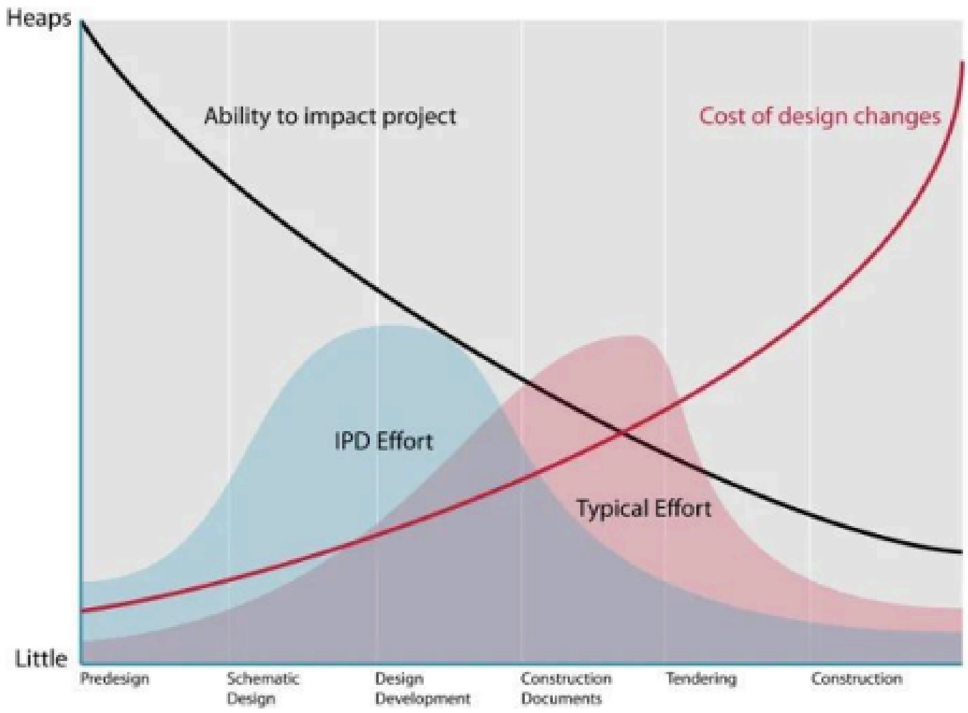

Figure 2.3: The MacLeamy curve illustrates the relationship between efficiency and costs due to design changes. Reprinted from MacLeamy, P. (2004).

Further on, the MacLeamy Curve in Figure 2.3 presents the relation between decision timing and project performance. It illustrates that the cost of design changes increases significantly as time passes in the project and the ability to influence the project outcomes decreases over time (Ilozor & Kelly, 2012). Although the curve is associated with BIM and Integrated Project Delivery, it emphasizes that if reliable data is available in early stages of a construction project, project managers are more prone to address risks proactively, detect anomalies and prevent schedule delays and cost overruns.

2.3 Digital transformation in the construction industry

The increased complexity of projects, challenges in productivity, and the need for improved information integration are a few of the driving forces behind the ongoing digital transformation in the construction industry. Currently, the construction industry is falling behind other industries in adopting digital technologies due to the fragmented structure, project-based environment, and conservative resistance towards organizational changes. Because of the above-mentioned challenges, construction companies need to adapt to new technologies to withstand their competition within the industry. Therefore, the principles of Industry 4.0 have taken off in the architecture, engineering, and construction industry as the concept of Construction 4.0. The concept suggests the use of technologies such as AI, BIM, Internet of Things, automation, and data-driven processes. These technologies enhance the efficiency and coordination across the project lifecycle (El Jazzar et al., 2020).

However, while the Construction 4.0 concept emphasizes fundamental efficiency, automation, and process optimization, Industry 5.0 highlights the focus on the human. There is a growing shift through digital technologies to include tools to enhance worker well-being, enable proactive safety management, and support human decision-making rather than maximizing efficiency, automation, and optimization. According to Zou & Ma (2025), DTs can significantly improve human-centered values and enhance safety management through facilitating risk assessment, real-time monitoring, and fact-based decisions. This provides a conceptual link between the concept Construction 4.0 and the emerging Construction 5.0.

2.4 Concept and definitions of digital twins

The concept of DTs has grown rapidly across multiple sectors over the past decade (Fuller et al., 2020; Kritzinger et al., 2018). Looking historically, the initial ideas of a DT concept can be traced back to the aerospace industry in the 1960s. However, it was not until 2010 that a practical definition emerged and marked its transition from an engineering approach to an established research concept (Shafto et al., 2010). The exact definition of what the DT concept implies, however, remains evolving and varies between and within different sectors.

Research-wise, when searching for DT studies in Web of Science, research interest in DT concepts and technology took a steep turn in 2017 and has continued to increase exponentially until today. When taking a closer look at the main themes of the articles published in 2017 and 2018, a convincing majority of them are related to the production and manufacturing industries. This points out the industrial and manufacturing sectors as the primary context in which the DT concept was first broadly established and matured.

Some articles from these years also highlight the DT concept as a key technology in the evolution of “Industry 4.0” and “smart manufacturing” (Schleich et al., 2017; Qi & Tao, 2018). According to Tao et al. (2019), the main contributions and applications of DTs in industry are to enable real-time cyber-physical integration, support data-driven decision-making, and enhance prediction, optimization, as well as gaining better control of an asset or product’s life cycle. Thus, their definition of a DT can be summarized as a digital representation of a physical system that continuously connects to its virtual model through real-time data. This aligns well with the digital transformation of manufacturing that Industry 4.0 entails, including integration of smart technology, automation of processes, and reliance on real-time data for decision-making procedures.

When adding the construction sector into the context, research articles started to emerge a few years later, in 2019 and 2020. The first construction-related DT articles were framed around facility management, operations, monitoring, and maintenance rather than project management during design and construction (Reja et al., 2024; Sacks et al., 2020). However, during recent years, DTs have increasingly been recognized as a promising tool for enabling proactive project management during the construction phase, rather than being limited to facility management purposes (Reja et al., 2024; Su et al., 2023; Yang et al., 2025). To further simplify the definition of DT and illustrate how the concept applies to construction, Sacks et al. (2020) provide a well-explained definition.

> *Digital twins are generally understood as up-to-date digital representations of the physical and functional properties of a system, which may be a physical instrument (e.g., an aircraft engine), a social construct (e.g., a stock market), a biological system (e.g., a medical patient), or a composite system (such as a construction project, with aspects of physical products and social systems)* (Sacks et al., 2020, p. 2).

This definition and distinction also help explain why DTs are more widely used and mature in facility management than in project management. In operation, a building can be treated as a physical instrument to be monitored and optimized. During project execution and project management, however, DTs must also account for social systems and human interaction, as construction projects depend on human actors, organizational arrangements, and decision-making processes in addition to physical products. This added complexity makes implementation in project-based environments more challenging.

2.4.1 Digital twin maturity levels

Although the DT technology seems to have the potential to improve efficiency, reduce costs, and avoid errors, its application within project management and the execution phase is still at an early stage. A major reason for the modest implementation is that it’s not integrated into traditional workflows, lacking both standardized guidelines and principles (Yang et al., 2025). To address this, Yang et al. (2025) suggest a maturity assessment framework to support effective implementation. The five-level DT maturity framework is illustrated in Table 2.1.

Table 2.1: Digital maturity levels, modified from Yang et al. (2025).

Maturity levels	Name	Definition
I	Basic level	The first level of maturity provides the basic functions and is limited. The digital twin is static because it lacks a structured collaboration network. Thus, this leads to inefficiency in communication and management.
II	Connected level	In the second level, it captures changes that are time-related and behaves in a more dynamic way. Compared to level I, this level offers a collaboration network leading to enhanced communication.
III	Integrated level	In the third level, the digital twin becomes more integrated through non-isolation of data collection, and there is a bidirectional communication with the digital twin and physical assets. This makes the digital twin utilize functions such as remote-control functions, real-time monitoring, and feedback mechanisms.
IV	Interactive level	The fourth level, the digital twin provides a more detailed model as well as accuracy. In contrast to the previous steps, it can perform predictive analysis through interaction and feedback loops together with physical objects.
V	Autonomous level	The fifth and last level of maturity, the digital twin utilizes machine learning and deep learning to interact and produce feedback with physical objects. At this stage, it performs automated predictions, optimizations in time, cost, and resource use, as well as autonomous decisions.

2.4.2 Digital twin approaches and data acquisition methods

In today's construction market, DT concepts mainly appear through two data capture approaches. One is built on laser scanning or LiDAR to produce detailed geometric models of the as-built environment by integrating high-resolution 3D point clouds with BIM (Algadi et al., 2025; Mirzaei et al., 2022). Meanwhile, the alternative approach uses 360°-images and vision-based techniques to generate vision-based DTs that emphasize site visualization and progress monitoring, offering an image-driven alternative to scan-based DTs (Pal et al., 2023; Zhou et al., 2025).

These two approaches represent the main practical implementations of the DT concept in the construction industry today. The approaches' primary differences lie in their balance between geometrical precision and visual detail richness. Thus, depending on the intended use of the DT, each approach presents different strengths and limitations. Subsections 2.4.2.1 and 2.4.2.2 further introduce these approaches, including how they work, what they can contribute to, their strengths and limitations, and their potential applications in construction. Finally, subsections 2.4.3 and 2.4.4 present Dalux's "Reality Capture" and "SiteWalk" concepts along with the Buildots platform, illustrating two concrete DT concepts that are practically applied in today's construction industry.

2.4.2.1 LiDAR- and laser-scanned Digital twins

LiDAR- and laser-scanned DTs are characterized by high spatial accuracy. The geometry-driven technology relies on three-dimensional point clouds to capture the physical properties of buildings and infrastructure (Drobnyi et al., 2023; Mirzaei, et al., 2022). This approach of using terrestrial laser scanning or mobile LiDAR systems enables the as-built conditions of an asset or building to be captured directly from the physical environment, often without relying on existing design documentation. This makes laser-scanned DTs particularly useful for existing or poorly documented structures (Algadi et al., 2025).

LiDAR- and laser-scanned DTs are commonly generated through scan-to-BIM or scan-to-model workflows, in which point cloud data are gathered and structured into digital representations (Banfi et al., 2022; Drobnyi et al., 2023). However, these DTs typically contain limited information beyond the building elements' shape and position. In addition, they are updated periodically rather than continuously, which reduces their support for real-time interaction with the built environment (Algadi et al., 2025; Mirzaei, et al., 2022).

A strength of LiDAR- and laser-scanned DTs is their ability to provide accurate and objective representations of as-built conditions. This could provide a basis for generating as-built documentation and supporting objective progress monitoring and performance assessment (Puri & Turkan, 2020). This high level of geometric accuracy provides a foundation for simulation, structural assessment, and data-driven decision-making across an asset or building's lifecycle (Algadi et al., 2025: Drobnyi et al., 2023; Mirzaei et al., 2022). As a result, LiDAR- and laser-scanned DTs are particularly suitable for facility and lifecycle management applications, including asset documentation, maintenance planning, and long-term condition monitoring (Banfi et al., 2022; Drobnyi et al., 2023; Khallaf et al., 2022; Opoku et al., 2021).

However, the literature points out several limitations of this approach to be used for project management during the execution phase. Capturing and processing LiDAR and laser data can be time-consuming and costly (Drobnyi et al., 2023; Zhou et al., 2025). This is a limitation, especially when frequent updates are required. Furthermore, the primary focus on physical geometry results in these DTs providing limited insight into social systems, human behavior, and organizational dynamics, which are central activities to construction project execution (Sacks et al., 2020).

2.4.2.2 360°-image and vision-based Digital twins

360°-image and vision-based DTs are an approach that relies on visual sensing technologies. The approach is built on a combination of 2D images, 360° panoramas, video streams, and CV techniques to visualize and monitor the construction environment (Pal et al., 2023; Shinde et al., 2023). In contrast to geometry-driven DTs that prioritize spatial and geometric accuracy, as discussed in subsection 2.4.2.1, vision-based approaches focus on visually capturing site conditions, construction progress, and ongoing activities to support monitoring and decision-making (Pal et al., 2023; Yang et al., 2024).

To generate a 360°-image and vision-based DT system, data are collected using 360° cameras, fixed or mobile cameras, and unmanned aerial vehicles. Using a combination of these technologies enable to capture of panoramic images and/or videos of construction sites at regular intervals (Shinde et al., 2023). Multidirectional, 360° imagery helps to provide better comprehensive visual coverage from single viewpoints, compared to conventional single-view images (Shinde et al., 2023). This reduces the risk of facing blind spots and improves the completeness of site documentation.

Vision-based DTs generally rely on CV techniques to perceive and interpret site conditions in near real time and align observed states with reference models, such as BIM (Pal et al., 2023; Zhou et al., 2025). The gathered visual data is processed using CV and machine-learning techniques, such as object detection, semantic segmentation, and activity recognition, to extract information about objects, progress, materials, equipment, and ongoing work activities (Koulalis et al., 2022; Pal et al., 2023). Thus, by comparing the observed visual states with expected states derived from BIM and schedules, vision-based DTs enable automated or semi-automated progress tracking and deviation detection to support construction monitoring and control (Pal et al., 2023).

In contrast to LiDAR- and laser-scanned DTs, vision-based approaches emphasize state recognition and appearance-based comparison rather than precise geometric reconstruction of the built environment. This focus enables higher update frequencies and lower data acquisition costs (Pal et al., 2023; Yang et al., 2024; Zhou et al., 2025). However, Zhou et al. (2025) point out that recent studies speak to the fact that acceptable spatial representation can still be achieved for many monitoring applications, especially if multiple cameras and sensing strategies are used together.

A major strength of 360°-image and vision-based DTs is their cost-effectiveness and scalability possibilities compared to laser-scanning approaches (Shinde et al., 2023; Zhou et al., 2025). Additionally, by using visual sensing and automated CV techniques, these systems can support more frequent assessment and updates of site conditions and thereby improve construction monitoring (Pal et al., 2023; Zhou et al., 2025). These characteristics together make this approach particularly suitable for dynamic construction environments. In addition, these are fundamental prerequisites to economically and functionally motivate DT concepts to be used for project management during the construction phase.

Another benefit of a vision-based approach is the contextual richness and appearance-based information (Koulalis et al., 2022; Pal et al., 2023; Shinde et al., 2023). This includes capturing workspace organization, safety conditions, and ongoing construction activities that are difficult to capture and represent by only using geometric-driven models. In turn, this supports applications including progress tracking, safety monitoring, remote site walks and inspection, and improved communication with stakeholders, where an understanding of site conditions and operational states is essential (Pal et al., 2023; Shinde et al., 2023).

From a sector development perspective, vision-based DTs are also closely aligned with AI-driven data analytics, as visual data can be automatically processed and interpreted using machine-learning and CV techniques (Pal et al., 2023). This alignment creates favorable conditions for the broader adoption of AI use in the construction industry. Thus, vision-based approaches support the implementation of DTs that prioritize continuous perception, data interpretation, and decision-support over high geometric accuracy (Yang et al., 2024).

Despite the advantages highlighted above, vision-based DTs also come with several limitations. The most obvious one is lower geometric precision compared to LiDAR- and laser-scanned approaches (Pal et al., 2023; Yang et al., 2024). Thereby, the vision-based approach is not suitable for applications that require precise dimensional measurements or tolerance control. Furthermore, its reliance on visual data also means that it is sensitive to lightning conditions, camera placement, and environmental variability, which can harm CV performance and result accuracy (Koulalis et al., 2022; Shinde et al., 2023).

In summary, 360°-image and vision-based DTs present a context-rich, scalable, and cost-effective approach to DT implementation in construction (Pal et al., 2023; Shinde et al., 2023). While this approach lacks the geometric precision that LiDAR- and laser-scanned approaches offer, its higher update frequency, lower implementation cost, and compatibility with AI-driven analytics make it suitable for construction-phase monitoring and decision-support (Pal et al., 2023; Yang et al., 2024). A comparison with the main characteristics of LiDAR- and laser-scanned and 360°-image and vision-based DTs is given in Table A.1 in Appendix.

2.4.3 Dalux's "Reality Capture" and "SiteWalk" concepts

Dalux is a software platform primarily used as a BIM viewer in the construction and real estate industry, developed with the fundamental idea of streamlining projects through digital models, drawing management, and field tools (Dalux, n.d.). Apart from Dalux as a BIM viewer, the software also offers, for this study, two relevant concepts: "Reality Capture" and "SiteWalk".

The Reality Capture concept enables the user to visualize the project by uploading point cloud data supported by laser scanners or 360°-images, which enables the environment to be visible alongside the BIM model. On the other hand, the SiteWalk concept enables visualization of the construction site with 360°-degree imagery. This, for example, enables the users to identify discrepancies between planned and actual conditions on-site, but also provides the opportunity to create and assign an issue or uncertainty directly to the person in charge (Dalux, n.d.).

2.4.4 Buildots – "Performance-driven construction management"

Buildots is a platform that offers a practical implementation of vision-based DT technology during the execution phase to support monitoring, progress tracking, and production management (Buildots, n.d.). The platform uses a combination of 360°-image capture, CV, and BIM integration to enable automated comparison of the as-built environment with the as-designed model and the project schedule (Buildots, n.d.; Shahpari, 2025).

Similar to the Dalux SiteWalk concept, site personnel collect visual data using 360° cameras (Buildots, n.d.). When uploading the 360°-imagery to the platform, AI-based algorithms help to analyze the images and recognize building elements by comparing them to the as-designed BIM model (Vuoria, 2024; Pasanen, 2024). The platform then allows the analyzed data to be accumulated into dashboards and visualizations that give project teams an overview of, for example, completion levels, installation accuracy, and potential deviations from the planned timeline (Buildots, n.d.; Vuoria, 2024). Such a support tool would help construction managers to obtain a more objective and data-driven understanding of site conditions compared to traditional manual reporting methods (Martikainen, 2025).

From a DT perspective, what Buildots offers closely aligns with the characteristics of a vision-based approach discussed in subsection 2.4.2.2. The platform focuses on visual recognition of construction elements and their completion status rather than geometric precision (Shahpari, 2025). Furthermore, integration of CV algorithms can help detect objects in the imagery and compare them with the BIM model to determine installation progress and identify potential deviations between the planned and actual state of construction (Wilson et al., 2024; Shahpari, 2025).

As discussed in subsection 2.4.2.2, vision-based DT approaches come with limitations and challenges related to their reliance on visual data. For Buildots, more specifically, however, detection is limited to elements that are both visible in the images and represented in the BIM model. An example, highlighted by Pasanen (2024), was that electrical cabling installations could not be monitored because such components were not represented in the BIM model. Although analysis is automated, manual site walks are still needed to collect the image data (Vuoria, 2024).

However, despite the many promising capabilities of vision-based monitoring systems, such as Buildots, the number of peer-reviewed studies that specifically evaluate these platforms remains limited. The literature found, directly highlighting Buildots, is either student theses or reports published by the company itself. As such, it is unclear how the AI and CV mechanisms actually work.

2.5 Digital twins during the construction phase

As mentioned in Section 2.4, DTs have been increasingly recognized during the execution phase in project management practices in recent years. In Figure 2.4, DT applications in construction project management are presented by Reja et al. (2024). Rather than focusing broadly on construction project management domains, this study is narrowed to construction progress monitoring, schedule and cost control, quality management, and safety management, as these application areas are most closely associated with the construction phase.

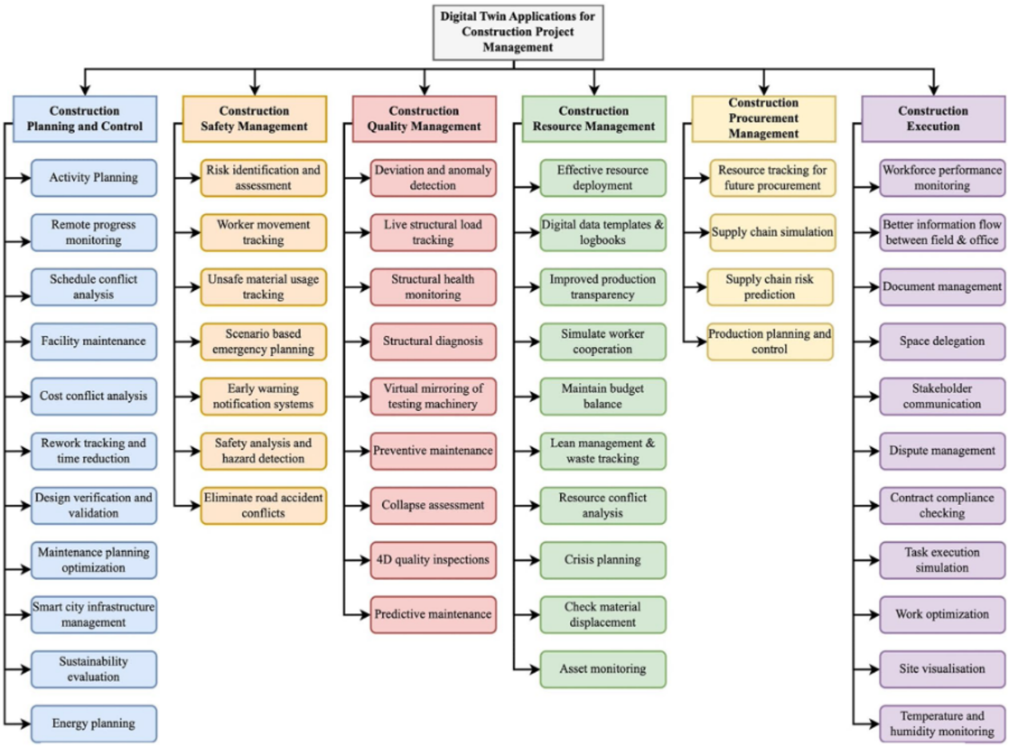

Figure 2.4: Digital twin application areas within project management. Reprinted from Reja et al. (2024).

2.5.1 Construction progress monitoring

The first application area in the execution phase is in construction progress monitoring and is conducted through a comparison between planned construction and actual on-site progress by updating the digital model with real-time site data. According to Reja et al. (2024), there is a potential to enhance data-driven project reporting and information transparency, which is identified as a major core feature of DTs in construction project management. Correspondingly, Yang et al. (2024) point out that DTs can support real-time tracking through integrated data acquisition. Combining these studies demonstrates a significant potential in progress awareness, simultaneously identifying challenges in data accuracy and requirements to keep an up-to-date model in a continuously changing environment.

2.5.2 Schedule and cost control

The second area of application, DTs can be applied in scheduling and cost controls during the construction phase. Reja et al. (2024) imply that DT projects enable project managers to identify deviations and budget overruns at an early stage through continuously updated project information linked to planning models. Further on, Yang et al. (2024) also enlighten that DTs enhance a continuous response between project schedules and site conditions through adaptive planning and control. Even though there are advantages, high quality of data integration, processes concerning costs and real-time updates must be well-defined for a beneficial implementation of DTs (Reja et al., 2024; Yang et al., 2024).

2.5.3 Quality management

Quality management is the third application area within DTs and can be applied through intelligent and proactive quality controls. The previous reliance on post-construction inspections can be exchanged for a comparison between as-designed and as-built integration in the digital model. By integrating quality management systems into DTs, Yue et al. (2025) highlight benefits such as defect detection, deviation identification, and "continuous and proactive quality assessment through comparison between planned and observed construction states. The study further demonstrates that, during the construction phase, DTs improve the accuracy of quality assessments by detecting geometric deviations and inconsistencies between as-built conditions and the drawings while construction is still in progress. However, the study also points out that the practical implementation is challenging due to the complexity of data acquisition, but also the effort to maintain the digital model up to date in a continuously changing construction environment. Furthermore, Yue et al. (2025) noted that a comprehensive implementation of a quality management DT is limited due to costs and effort related to data acquisition technologies and system integration.

2.5.4 Safety management

Further on, since construction is recognized to be one of the most fatal industries, recent research has increasingly explored how DTs can support construction safety management by enabling more proactive risk prevention and hazard identification. According to Han et al. (2025), by incorporating sensors to capture on-site data, vision-based systems, and other data sources such as positioning systems, wearable devices, and equipment operation data, DTs can predict dangerous circumstances and enhance awareness across different scenarios. Simultaneously, the study is putting weight on issues such as practical implementation due to data integration, system complexity, and keeping an up-to-date digital model in a dynamic environment as the execution phase is (Han et al., 2025).

2.6 Integration of AI in digital twin frameworks

While Section 2.4 reviewed the application areas of DTs during the execution phase, this section focuses on AI as an enabling technology. Rather than introducing new use cases, the purpose of this section is to explain how AI allows DTs to interpret data, automate analysis, and support decision-making in dynamic construction project environments.

Construction projects operate in highly dynamic environments where on-site conditions change from day to day. DTs can then be used to visualize and continuously collect large amounts of data as the environment evolves. However, advanced analytical capabilities are required in order to turn the gathered raw data into information that is both meaningful and practical. Because of this, it becomes desirable to incorporate AI into DT frameworks to increase their processing power and thereby expand their applications. Kreuzer et al. (2024) argue that by facilitating predictive analysis, deviation detection, and optimization, all of which are essential for informed decision-making, AI allows DTs to move beyond static representations.

In addition to data processing, AI can assist in mitigating cognitive overload by collecting and identifying relevant decision-making signals (Laamanen et al., 2025). Instead of overwhelming project managers, AI-driven DTs can help highlight deviations and risk indicators. In dynamic and rapidly changing construction environments, AI is claimed to improve attention capacity by helping with structuring and filtering data inputs and then transferring that into manageable insights (Laamanen et al., 2025). This function is particularly important for maintaining situational awareness in environments characterized by time pressure and uncertainty.

Furthermore, AI image recognition can offer automated recognition of objects and progress monitoring by interpreting visual data and observing site conditions (Hsieh et al., 2026). By relating real-time observed states to reference information derived from, for example, BIM models and schedules, AI can support continuous interpretation of construction progress without relying solely on manual reporting (Hsieh et al., 2026; Pal et al., 2023). Despite their proven potential in academic literature, AI-based interpretation methods are still mostly investigated through research prototypes and pilot deployments. This demonstrates early maturity of these systems in practical construction settings (Hsieh et al., 2026; Pal et al., 2023).

Additionally, by identifying trends, discrepancies, and variations between reference data and observed on-site conditions, AI can make it possible to automatically evaluate construction data (Yue et al., 2025). AI enables continuous analysis of as-built data through learning-based algorithms, eliminating the need for traditional manual, element-by-element comparison. This enables deviations to be identified and understood instantly (Yue et al., 2025).

When combined with DT systems, AI can, in addition to detecting deviations, accelerate feedback loops. By continuous comparison of real-time site data with planned BIM models and schedules, AI can enable faster and more efficient reassessment and monitoring of project progress. Laamanen et al. (2025) argue that AI can support “shifts in attention” in evolving and changing environments by providing more rapid feedback. For construction projects, this would allow project teams to respond to changes earlier and adjust plans more efficiently, thus moving from reactive to more proactive workflows. However, worth adding to this discussion is that although AI strengthens analytical capabilities, it does not remove uncertainties embedded in construction projects from decision-making. Laamanen et al. (2025) point out that AI can help reduce some cognitive limitations, although human judgment remains necessary. AI should therefore be understood and utilized as a decision-support tool rather than as a replacement for managerial expertise.

A more concrete example of an AI application that has been reviewed across various studies and papers is improving on-site safety. By examining and analyzing heterogeneous data, such as images from construction sites, AI can enable automated interpretation of safety-related information. In dynamic construction environments, AI also enables predictive analysis and the identification of potential hazards by recognizing patterns, deviations, and risk indicators over time (Han et al., 2025; Omrany et al., 2023). Instead of replacing human decision-making regarding safety in this situation, AI may serve as an analytical layer that improves situational awareness. However, the literature notes that environmental complexity and the difficulty of keeping an accurate and current digital model in a dynamic environment make AI implementation still difficult (Omrany et al., 2023).

In summary, construction projects operate in dynamic environments where site conditions change from day to day. Given these conditions, Laamanen et al. (2025) highlight AI systems as key enablers of adaptive implementation by supporting continuous adjustments during project execution through ongoing monitoring and faster feedback loops. Combining AI with DT frameworks can, in turn, enable continuous reassessment of project status instead of relying on manual periodic reporting and updates, which enables project managers to act more responsively, proactively, and adaptively while saving time.

2.7 AI prompting

A prompt is the primary method to interact with a generative AI system. According to Schulhoff et al. (2025, p. 5):

> *A prompt is an input to a Generative AI model that is used to guide its output. Prompts may consist of text, image, sound, or other media... Prompts usually have some text component, but this may change as non-text modalities become more common.*

This definition shows that prompting is the main way to interact and communicate with an AI system. The relevance of the AI-generated output is thus influenced by the inserted prompts' content and structure. Clear, specific, and well-structured prompts, thus, tend to lead to more accurate and relevant outputs. Therefore, prompting is argued to be an increasingly important skill to master for guiding AI systems to generate useful outputs without modifying the underlying AI model itself (Robertson et al., 2024; Schulhoff et al., 2025).

Prompting can be seen as a collaborative process and communication channel between the user and the AI system. Therefore, the effectiveness of this interface depends on both the users' ability to provide a meaningful prompt and the AI system's ability to understand and interpret them appropriately (Robertson et al., 2024). Besides being a straightforward technical input, prompting can be seen as a way of directing the AI system's attention and focus. Laamanen et al. (2025) argue that prompts influence how the attention of AI systems is directed by shaping what information is processed and prioritized. Thus, prompting also shapes the analytical focus of the AI system, besides retrieving and interpreting certain information.

This perspective becomes particularly relevant in DT environments with large volumes of heterogeneous data. When using the DT with integrated AI, the users' prompts influence how data are handled and interpreted (Laamanen et al., 2025). For example, a prompt centered on safety may prioritize identifying risk factors and potential hazards on-site. In this way, prompting can shape how DT systems can be applied to support future decision-making and project management practices. In addition, a prompting approach allows various divisions to tailor the output to their own needs. This enables multifunctional use of the DT, where the main contractor, as well as the subcontractors, can use it depending on each division's informational needs and responsibilities.

However, if not carefully created, prompts also risk introducing bias. Laamanen et al. (2025) highlight that framing, which prompting somehow implies, affects how attention is allocated and how potential problems are interpreted. If a prompt focuses on certain variables while overlooking others, the AI output will be colored by this imbalance. This can be seen as concerning in a DT and project management context since it risks leading to unconsciously prioritizing specific risks or performance measures, and potentially overlooking other relevant factors. Human judgment will therefore remain important for this type of AI application. This, in turn, further underscores the importance of carefully structured prompt designs.

In summary, the value of prompting within DT and AI-integrated frameworks largely depends on how effectively human users can engage with the AI-generated insights to support informed decision-making. Even though AI can automate tasks such as interpreting data and detecting deviations, these capabilities are only as good as the prompts guiding them and the critical judgment of the outputs (Laamanen et al., 2025; Reja et al., 2024; Yang et al., 2024). Prompting should therefore not only be seen as a technical input mechanism, but also a cognitive and organizational practice that shapes how AI is applied and integrated into management processes.

2.8 Computer vision and contextual interpretation

According to Alamri & Pugeault (2020), CV is a system whose function is to interpret and detect objects in images or videos. Traditionally, object detection was performed through the identification of their visual appearance alone and not their contextual information. Contextual information focuses not only on the object alone, but also considers the relationships between objects and the environment. It includes: semantic, spatial, and scale context. These relationships contribute to information that improves the detection accuracy and environmental understanding of the object itself. In addition, objects are simpler to identify when presented within their natural context rather than separated in isolation, as contextual information helps to reduce ambiguity and improve categorization accuracy. The contextual interpretation allows AI to understand relationships between those objects. In DT environments, such potentials can support project managers with real-time monitoring and decision-making through data analysis from various objects and activities in the execution phase (Reja et al., 2024; Yang et al., 2024).

Firstly, the semantic context specifies the probability of objects occurring together in the same environment and is dependent on co-occurrence patterns, which means that certain objects have a higher probability to occur in the same environment than others (Alamri & Pugeault, 2020). By integrating the semantic relation, AI can minimize the ambiguity of object detection and improve the recognition accuracy. This context also adjusts the confidence levels by increasing the probability of objects that belong to the environment and reducing those that do not (Alamri & Pugeault, 2020).

Secondly, the spatial context explains the positional relationships between an object and the environment. Spatial context refers to the probability that a certain object is in a certain position and arranged relative to other objects brought along. This relationship will assist AI to understand how objects are usually placed in relation to each other, thereby reducing recognition errors and improving detection performance (Alamri & Pugeault, 2020).

Lastly, the scale context refers to the relative size of objects in an environment, as it considers the size of an object compared to another. By analyzing these size relationships between objects, AI can both better understand the environment and detect objects that appear misplaced or unreasonable (Alamri & Pugeault, 2020).

2.9 Literature summary and research gaps

When summarizing the reviewed literature, it can be established that the construction industry and its projects are characterized by complexity, uncertainty, and fragmented information flows (Gomez-Cabrera et al., 2024; Lafhaj et al., 2024; Purushothaman et al., 2024). When evaluating the main causes of three major problems in the industry, including safety concerns, cost overruns, and delays, joint root causes during the execution phase can be traced back to a lack of situational awareness of on-site conditions and poorly or inefficiently executed management practices (Abdelalim et al., 2025; Gómez-Cabrera et al., 2024; Kinga Wasilkiewicz et al., 2024; Lafhaj et al., 2024; Purushothaman et al., 2024; Samuelsson, 2025; Smita & Bhole, 2016; Tafesse, 2021).

In response to these challenges, the theoretical concept of DTs appears as a promising support-tool. Through capabilities of improving transparency, on-site visualization, and near real-time progress monitoring, DTs have the potential to strengthen decision-making and coordination in construction projects (Reja et al., 2024; Su et al., 2023; Yang et al., 2025). Among the two main DT concepts and data acquisition methods, vision-based twins appear most suitable for project management applications during the execution phase. This approach's scalability and relatively low resource intensity allow for more frequent data updates, which make it well aligned with the dynamic nature of construction projects (Koulalis et al., 2022; Pal et al., 2023; Shinde et al., 2023; Yang et al., 2024; Zhou et al., 2025).

However, vision-based twins generate a large volume of heterogeneous data that needs to be interpreted and structured before they can support managerial decision-making. This is where the strength of AI comes into play, enabling automated interpretation, deviation detection, and predictive capabilities (Han et al., 2025; Hsieh et al., 2026; Laamanen et al., 2025; Omrany et al., 2023; Yue et al., 2025). The usefulness of the AI-integrated DTs becomes even more powerful when considering prompting techniques as an approach that allows various divisions and stakeholders to tailor data outputs to their specific informational needs (Laamanen et al., 2025; Reja et al., 2024; Robertson et al., 2024; Schulhoff et al., 2025; Yang et al., 2024). Thus, such an approach increases the practical relevance of the DT, potentially extending its value beyond the main contractor to subcontractors and project actors.

Despite the concept sounding promising in theory, the combined application of vision-based DTs, AI-integration, and prompting remains limited in practical project management contexts. Existing literature often addresses these technologies separately rather than as an integrated solution tailored towards project management and execution phase practices. This literature review is, to a large extent, a puzzle that has been laid to show how combining the strengths of multiple technologies can tailor its use. Thus, a gap exists in understanding how these technologies can be combined to improve control of construction site operations. The empirical data are therefore particularly important for evaluating this theoretical framework. This thesis aims to fill this gap by exploring how AI-integrated, vision-based DTs can be integrated to support project management practices during the execution phase.

2.9.1 Identified research gaps

Despite the potential, several research gaps remain uncertain. The literature about DTs has traditionally focused on facility management and life cycle optimization rather than the construction phase (Opoku et al., 2021; Sacks et al., 2020). However, recently, literature has acknowledged the relevance of DTs in the execution phase as well (Reja et al., 2024; Yang et al., 2025). Unfortunately, the empirical research is limited, suggesting that day-to-day project management activities can benefit from these practices. In particular, the uncertainty of how the DT can interpret information, such as support monitoring, coordination, and decision-making in a dynamic environment with continuous changes.

Further on, the literature is primarily concentrated on the technical system development, including conceptual structures, data acquisition, and CV-based analysis techniques (Kritzinger et al., 2018; Mirzaei et al., 2022; Zhou et al., 2025). Although the technical system development is essential, few literature studies investigate how the user's point of view is and the organizational perspective of project management. However, construction projects are not solely demanding of technical systems. Projects are also demanding on social and organizational systems, such as different stakeholders, temporary teams distributed with different responsibilities (Sacks et al., 2020; Lafhaj et al., 2024). Thus, the limitation of social and organizational integration creates a gap between technical potential and practical adoption. Therefore, to establish a successful implementation, the understanding of how project managers, site managers, and supervisors interpret, perceive, and utilize the DT is vital.

2.9.2 Positioning of the present study

Given the current state and experience of DT application in the construction industry and in response to the identified gaps, this thesis will further explore its potential for project management practices within the construction phase. In order to address the characteristics of a construction environment, with time and cost constraints, focus will be on a vision-based DT approach, which, according to the reviewed literature, is argued to be better suited for management practices during the execution phase. This approach's scalability capabilities, together with being less resource-intensive, resulting in more frequent update cycles and more economically justifiable, motivate this direction.

However, most importantly, this thesis has its starting point in the user perspective, which sets it apart from most existing literature. Many studies are based on theoretical frameworks and technological development, reflecting the early stage of implementing DT concepts in project management during the construction phase. Therefore, the focus of this study lies in evaluating thoughts, needs, and requirements from the users, thus, the managers who are intended to utilize the technology. By adopting this approach, the thesis aims to align and streamline the technology development with actual user needs and desires in mind.

To further strengthen the practical usefulness and relevance of this emerging technology, and to align it with current technological developments and trends, this study also explores the potential of integrating AI to enable semi-automated and fully automated functionalities and workflows within the proposed framework. As highlighted in the reviewed literature, AI in combination with CV and prompting provides a promising foundation for streamlining project management practices during the construction phase, while also enabling various disciplines to tailor the outputs of the DT to their specific needs and use cases.

By doing so, this study contributes to bridging the gap between conceptual DT research and practical project management applications in dynamic construction environments.

3
Methods

This chapter describes the methods used in the study and begins with Section 3.1, describing the research design, followed by Section 3.2, presenting the literature review process. Section 3.3 and its subsections describe the data collection processes, including preparations for interviews, the interviews themselves, and how they were conducted, Dalux user days and webinars, subcontractor workshop, and practical testing of the vision-based DT concept in combination with AI. Lastly, Section 3.4 discusses the ethical considerations, and Section 3.5 discusses the use of AI tools.

3.1 Research design

The study adopts an interpretive research philosophy, aiming to explore, understand, and interpret the potential of vision-based DT solutions for project management practices during the execution phase of a project, with the user perspective in focus. From an interpretive perspective, knowledge is generated through individuals' experiences, meanings, and perceptions of situations over time. Thus, with the user perspective as a central starting point, the study aims to capture how professionals would make sense of, evaluate, and potentially integrate such technological solutions within their daily workflows.

To achieve this, the study combines a literature review and a qualitative data collection consisting of interviews, site visits, Dalux webinars, Dalux user day, and practical testing of an AI-driven vision-based DT concept. This combination enables both theoretical grounding and empirical exploration of the subject. The study is motivated by the relatively low maturity level of these technologies and the limited understanding of how DTs can be simplified and effectively implemented in practice, particularly for the execution phase.

The study primarily follows an inductive research approach, meaning that existing literature serves as a conceptual foundation to define the scope of relevant project management practices and suitable DT data acquisition methods. The empirical data collection then aims to explore professionals' perspectives and thoughts on the literature findings, as well as their experiences of DT concepts in practice. Thereby, the literature review helps tailor and narrow down the focus of the interviews, while the findings are gathered through the interpretation of participants' experiences and reflections.

Furthermore, the study is designed as a qualitative case study, focusing on construction projects within Peab's project portfolio that use Dalux's "SiteWalk" concept. These cases provide a practical context in which a variant of a vision-based DT concept is used. However, this study does not explicitly evaluate the Dalux concept, but the cases serve as an empirical reference point to explore how similar solutions work in practice. Additionally, the cases allow for discussion about how these can be further developed, which this study aims to investigate. A comprehensive illustration of the research method is shown in Figure 3.1.

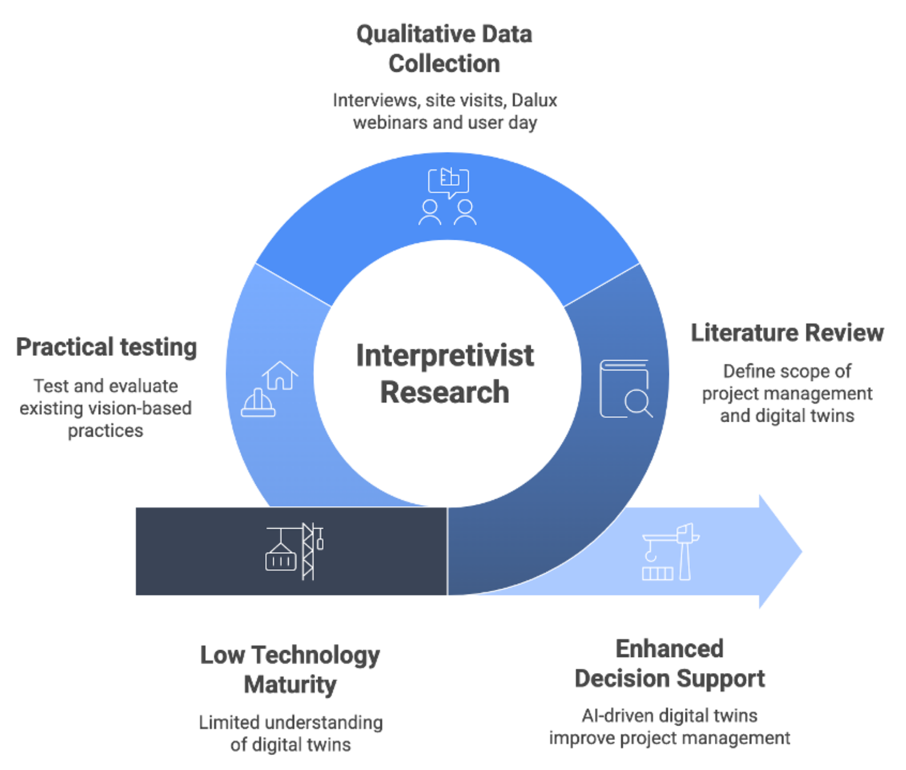

Figure 3.1: Illustration of the research method. Generated and modified in (Napkin AI, 2026).

As a summary, the research strategy can be divided into three fragments, including: a literature review that guided the direction of this study and identified the research gap within the subject, followed by interviews that collected data from the users' perspective, and lastly, practical testing that demonstrated how a vision-based DT solution, together with AI, can be used in practice.

3.2 Literature review

The literature review was carried out using a semi-systematic approach that combined structured methods with analytical flexibility. This enabled the exploration of relevant themes in an organized way while remaining receptive to new perspectives emerging within the field of DTs and advanced digital technologies in construction project management. Since the literature review aimed to build a conceptual foundation and guide the direction of empirical data collection, this semi-systematic approach was considered suitable.

The databases Web of Science, Scopus, and Google Scholar have been used as the primary search platforms to identify and gather relevant literature, including academic journal articles, conference papers, national and international statistics, and websites. Multiple searches have been conducted when shaping the literature review. Various combinations of keywords related to, for example, DTs, AI, vision-based technologies, and construction-phase project management have been used to tailor the search toward what is desired.

In addition, attention has been directed towards selecting recent publications, especially when reviewing literature on technological tools. This helped to ensure that the papers were up to date and that their content reflected current developments. Furthermore, peer-reviewed articles published in well-established academic journals were prioritized. Citation frequency of the papers and journal reputation have also been considered as indicators of academic impact and research quality. This literature selection strategy has been applied to strengthen the overall quality and credibility of the literature review and its theoretical foundation.

The literature review chapter is designed to introduce the reader to the broader industry context and step-by-step narrow down the scope of the study based on the insights gained from the reviewed literature. The chapter begins with discussions regarding current industry challenges within construction, including their underlying causes, and what is needed to mitigate these problems with a certain focus on technological and organizational measures. The review then narrows its focus to project management practices during the execution phase, as several of the identified challenges and their causes relate to management processes in this stage of a project.

In this context, the theoretical concept of DTs has been increasingly highlighted in the literature as a promising tool to help address such challenges by its capabilities of enhancing transparency, real-time monitoring, and information accessibility. However, while DTs are frequently discussed regarding application in design, planning, and facility management stages, their application as decision-support tools during the execution phase remains largely unexplored in comparison. Particularly, there is a notable gap in studies exploring a vision-based approach of DTs for project managers during project execution. Because of this lack of directly relevant research, it became necessary to piece together insights from different but related fields. Thus, the review compiles literature on execution-phase project management challenges, DT technologies and data acquisition methods, and AI capabilities, but not all articles are necessarily directly linked to the construction sector.

By combining and puzzling these aspects together, the literature review creates a foundation and conceptual framework to bridge a fragmented research landscape. Thus, instead of relying on established literature that precisely targets this application area, the literature review connects relevant theoretical insights to identify potential intersections between technological capabilities and managerial needs. As a result, the literature was identified through multiple structured searches using various combinations of keywords related to DTs, AI, vision-based technologies, and execution phase project management.

Given the exploratory nature of the literature review, with limited empirical research within this specific application area, the qualitative data collection phase becomes particularly essential. The interviews, workshop, webinars, exploration of the Dalux concepts, and site visits have therefore been important to contextualize, examine, and evaluate and relate the theoretical findings to a real construction project setting.

3.3 Data collection

As the study covers a relatively new concept and an emerging technology, both for the authors and in construction practice, there was a need to both test, evaluate, and explore potential future applications to enable a more nuanced discussion and analysis. By combining different approaches, a more comprehensive understanding of the concept of DTs was achieved, allowing the collected data to be related to both practical test and theoretical reasoning.

3.3.1 Exploration of Dalux's SiteWalk concept

To better bridge the gap between the literature review and the interview study, where Dalux's SiteWalk concept plays a central role, the platform was explored through hands-on interaction in a demo project environment. The purpose was to develop a practical understanding of the platform's usability and to identify core functional areas assumed to be relevant to the study and to discuss in the interviews.

In addition to reviewing and exploring pre-recorded SiteWalks in the demo environment, own SiteWalks were recorded and uploaded to gain further insight into the concept's user-friendliness and understand the practical effort and time required for recording and uploading. This understanding was crucial for assessing whether the benefits of SiteWalk outweigh the required resources and investments or not. Thus, this exploratory stage prepared the authors for the interviews, enabling a better grasp of the interviewees' perspectives and workflows.

3.3.2 Interviews

Building on the foundation from the literature review and exploration of the SiteWalk concept, a qualitative data collection through semi-structured interviews was conducted to further delve into the subject. The purpose of the interviews was to evaluate the theoretical findings and develop a wider understanding of how the DT technology is interpreted across different projects and disciplines.

As strengthened by Galetta (2013), a semi-structured approach is considered appropriate when needing to balance and combine structure with flexibility. This approach made it possible to systematically address key themes from the literature review while still allowing the interviewees to share their experiences openly and freely introduce new perspectives. This semi-open interview format gave room for slightly different discussions between the interviews and enabled the interviewees to pinpoint the aspects that they think were most relevant for their roles, disciplines, and experiences. This, in turn, contributed to a wider and more nuanced understanding of how DT technology is perceived and applied in practice.

The interviews will primarily be conducted with professionals from Peab and their subcontractors working in construction and management roles within projects using Dalux SiteWalk. These projects serve as valuable cases thanks to the possibility of deriving valuable insights from working with a sort of DT technology.

The primary aim of the interviews was to capture the experiences of professionals working in relevant roles in order to identify practical experiences, needs, and perceived challenges related to, for example, progress tracking, safety management, and decision-making in construction. The interviews also provided an opportunity to explore which DT functionalities are perceived as valuable and which are not. The interview data were analyzed thematically, through a method called coding, to identify recurring patterns and themes in the discussions. By gathering insights from potential users of a DT technology, the interview results aim to build a foundation to guide its development towards the users' needs and expectations through a co-creation approach.

A total of 7 interviews with 10 different participants have been conducted. An overview of the interviewees and their roles is presented in Table 3.1.

Table 3.1: Overview of the interviewees, their roles, and type of company.

No.	Title / Role	Company type	Reference in text
1	Site manager	Main/total contractor	INT1
2	Site supervisor	Main/total contractor	INT2
3	Project engineer	Main/total contractor	INT3
4	Site supervisor / project engineer	Main/total contractor	INT4
5	Project manager	Subcontractor	INT5
6	Customer success manager	Construction software provider	INT6
7	Customer success manager	Construction software provider	INT7
8	BIM-coordinator	Main/total contractor	INT8
9	Project director	Main/total contractor	INT9
10	Cost engineer	Main/total contractor	INT10

The interviews were conducted both in person and digitally through Microsoft Teams. By offering a digital alternative, the threshold for participation was reduced while also allowing the interviewees to be more flexible. This approach laid the foundation for gathering as many interviews and perspectives as possible. The interviews lasted between 30 and 60 minutes, most of which were recorded with participant consent to later be transcribed. The interviews were transcribed word by word to enable a thematic analysis. If the interviewee did not wish the interview to be recorded, careful notes were taken during the conversation instead. The contents in the interview transcriptions and notes were coded using AI, where recurring patterns, themes, and relationships guided the categorizing process. These categories were later used to guide the structure of the interview results chapter.

3.3.3 Workshop with a subcontractor

To complement the perspectives obtained from the interviews, a workshop was conducted with a subcontractor who had no prior experience with Dalux SiteWalk or similar visualization tools. The purpose of the workshop was to provide additional insights from a subcontractor perspective, as the majority of the interviews were conducted with representatives from a main contractor. Moreover, it also enabled a more open and exploratory discussion of potential use cases for SiteWalk, rather than focusing on evaluating existing practices and uses. This approach encouraged the participants to be more open-minded.

The workshop was conducted by the two authors together with three representatives from the subcontractor, representing a range of roles and levels of experience. Together, the participants covered roles and experiences ranging from tendering processes, sales, design, project management, cost control, and financial follow-up. Thus, the workshop facilitated both production-related insights and discussions, as well as broader project perspectives.

The workshop was structured as an interactive session that began with a short demonstration of the SiteWalk concept, including its main functionalities, followed by open-ended discussions. The demo was done to ensure that the participants had a common understanding, given their lack of prior experience with the tool.

The demonstration was followed by a discussion that was structured thematically related to different phases and aspects of construction projects, including design coordination, production planning, project management, and progress and cost control. Instead of focusing on predefined use cases, the participant were encouraged to reflect on their own work and current practices to try to identify potential areas where visual site data could provide concrete value. Importantly, the workshop participants were not shared the results from the interviews to not limit their reflections.

The workshop was intentionally exploratory and scenario-based to guide the participants to discuss both current challenges in their workflows and how a visualization tool, like SiteWalk, could potentially address these challenges. This facilitated a future-looking perspective which aimed to complement the more experience-based insights gathered from the interviews. Thus, the workshop served as an exploratory complement to the interviews with a particular focus on potential applications beyond current industry practices.

3.3.4 Dalux user day and webinars

Alongside conducting interviews and reviewing literature, industry events like the Dalux user day and selected webinars have been attended. These experiences gave practical insights into how software developers and professionals in the sector reason about technological developments, such as DT concepts and AI integration. Participating in the Dalux SiteWalk webinar was particularly valuable because it provided insight into Dalux's vision for how the SiteWalk concept can be used and where its main strengths lie. This vision was later discussed in the interviews with the Dalux representatives, in which the webinar shaped questions and guided the direction of the conversations. However, these events have not been used as primary sources of data. Instead, they have helped to better understand the industry's perspectives and technological trends. Notes and reflections from these sessions helped shape the interpretation of the findings from the interviews.

3.3.5 Practical testing of identifying safety hazards on construction sites using visual data and AI

To complement the literature review and qualitative data collection, practical tests were conducted to demonstrate the potential of combining visual site data, in the form of 360°-images, with AI for identifying safety hazards on construction sites. The 360°-images were collected from a real ongoing construction environment by recording a Dalux SiteWalk. The testing provides an example of how visual site data gathered by SiteWalk can be utilized beyond its current application areas identified in the interviews.

From the gathered on-site material, ten 360°-images, containing safety hazards, were manually selected. For each image, the manually identified hazard, serving as a reference outcome, was noted. These ten images formed the basis for the practical tests, enabling a comparative analysis between human-identified hazards and AI-generated assessments.

The selected images were processed in an AI-based data cluster at Chalmers University of Technology, ensuring that no data was shared with third parties. Within this environment, the analysis was performed using the GEMMS framework, developed and described by Yakupogullari et al. (2026). The GEMMS framework combines SAM3 and Gemma 3. While SAM3 is responsible for identifying and segmenting relevant objects within the images, Gemma 3 performs the analysis by interpreting the segmented outputs identified by SAM3. To enable this interpretation, structured prompts were introduced to define context, objectives, and evaluation criteria for the AI. These prompts guided how the model reasoned about the visual inputs by stating what to assess and how to evaluate different conditions.

A more detailed description of the GEMMS frameworks and the prompt design can be found on the developer's GitHub page (Yakupogullari, 2026).

3.4 Ethical considerations

This study touches on multiple ethical considerations related to data collection and the use of digital technologies for construction production. All interviewees and workshop participants were informed about the purpose of the study, clearly stated in a consent form that was sent out and signed by each participant before the interviews. The consent form also included an option to accept or deny the interview to be recorded and transcribed. The interviewees' participation was completely voluntary. All the gathered data was anonymized and stored on a shared Microsoft Teams channel between the authors. Note that, before utilizing AI for coding and categorizing, all interview transcriptions and notes were manually reviewed to remove any personal data, including names of the interviewees, companies, and projects.

Worth mentioning is that SiteWalk is not a standard practice in all Peab's projects. Instead, its implementation is driven by some particularly committed individuals in certain projects, meaning there is a risk of an overwhelmingly positive presentation of the concept in the interviews. To address this potential bias, the study has been supplemented with its own testing and reflection on the concepts, which has contributed to a more nuanced interpretation of the results.

In addition to the interviews, the study has included practical testing of the SiteWalk concept. As a part of the testing, own recordings were made, both in a static office environment and on an active construction site, with the aim of getting a better understanding of the functionality and use of the tool. These recordings have not been used as empirical analysis material linked to the interview study. Instead, it has primarily served as support for interpreting the interview results. In connection with the testing, however, image material from site was used to a limited extent to test AI-based analysis, with a focus on identifying general safety risks on the construction site, such as trip and struck-by hazards. The analysis has therefore focused on the physical environment and not on the behavior or working methods of individuals. No individuals have been the subject of analysis, and no personally identifiable material has been processed.

Meanwhile, the use of visual documentation tools, such as Dalux SiteWalk, implies that work environments where people can be present are captured. Although Dalux includes functions for anonymization, such as blurring people, ethical aspects related to privacy and the experience of surveillance remain. The study, therefore, addresses the technology from a user perspective and focuses on its function and application rather than on individuals' behavior.

Finally, the study concerns the use of AI as decision support in the construction process. An important note is that it is emphasized that AI should be perceived as a complement to human judgment rather than a direct replacement. This is particularly important in safety-critical contexts. Thus, detection of safety hazards with AI, described in subsection 3.3.5, should be seen as a complement to regular safety measures.

3.5 Use of AI tools

The use of AI in this thesis has served as a supportive tool to improve efficiency, clarity, and coherence of the writing process. For example, AI has been used to organize and structure the literature review, particularly in developing the reversed pyramid structure, with a broad introduction that was gradually narrowed to ensure relevance and maintain a coherent order. Furthermore, AI tools have supported with ensuring high grammar accuracy, spelling, and improving the overall flow. Moreover, an AI-based tool was used for generating an illustration of the research method and the proposed framework, although these were manually edited and adapted to better mirror the content. Lastly, Copilot, as part of Microsoft Teams, has been used to transcribe interviews conducted remotely, where the interviewees agreed to have the discussion recorded. Lastly, AI has been used for coding and structuring the interview contents thematically. However, note that before inserting the transcriptions and notes to AI, these were carefully manually checked to make sure they did not include any personal information, such as names, the company they worked for, or which project/projects they were currently involved in.

Importantly, AI tools have not been used to generate empirical data, produce full texts, or analyze findings. Additionally, as the findings of this study connected to AI integration imply, AI has been treated as a support tool that can not replace human judgment. As such, all AI-generated outputs were critically reviewed and interpreted to maintain high academic quality. Overall, AI has primarily served as a mechanism for enabling valuable feedback loops to refine structure, enhance content, and maintain coherence for improved readability.

Below is a list of used AI-tools and their contributions:

- ChatGPT: Structured the literature review with a broader beginning which is later narrowed down to ensure relevance and coherence. Coded the interview and workshop transcriptions and notes thematically, laying the foundation for the result chapter structure.
- Grammarly: Assisted with grammar, spelling and improved the overall flow of the text.
- Napkin AI: Create illustrations of the research method and the proposed framework.
- Copilot: Used for transcribing interviews conducted remotely. Built in AI tool in Microsoft Teams.
- GEMMS: Hybrid AI model used for the practical testing described in Section 3.3.5

4

Results

This chapter presents the results, with Sections 4.1 and 4.2 based on the authors' observations, while Sections 4.3, 4.4, and 4.5 present the results from interviews, workshop, and AI testing. Firstly, Section 4.1 demonstrates the findings from the Dalux SiteWalk concept, which evaluates functionality and practical application of the technology. Secondly, Section 4.2 presents the gained insights from the Dalux User Day as well as various Dalux webinars. Thirdly, Section 4.3 summarizes the results from the interviews, containing key perspectives and experiences shared by the interviewees. Fourthly, Section 4.4 presents the results from the workshop with a subcontractor. Lastly, Section 4.5 presents the result of combining visual site data with AI for identifying safety hazards.

4.1 Dalux' SiteWalk hands-on experience

To better bridge the gap between the literature review and the interview study, where Dalux's SiteWalk concept plays a central role, the platform was explored through hands-on interaction in a demo project environment. The purpose was to develop a practical understanding of the platform's usability and to try to identify core functional areas that were assumed to be relevant to the study and to discuss in the interviews. From exploring the SiteWalk concept, six particularly interesting takeaways were made, summarized in Table 4.1.

Table 4.1: Identified functional areas, system capabilities, and functional boundaries of the Dalux SiteWalk concept.

Functional area	System capability	Functional boundary
Time- and location-based 360° image documentation	Continuous visual site capture/documentation	No automated data interpretation
Spatial deviation tracking	Location-linked observation registration	No automated deviation detection
Real-time production data visibility	Cross-device site monitoring	No predictive or analytical capabilities
Documentation and reporting support	Structured traceability	No automated reporting analytics
Role-based collaborative access	Multi-actor transparency	No intelligent workflow automation
BIM integrated model connected to reality	Visual model alignment	No automated model validation

When exploring the platform and SiteWalk concept, it could be understood that it primarily functions as a digital support system within a construction project environment. The concept is built on 360°-image documentation, where the captured site materials are linked to locations in the floor plans or BIM models. This builds a structured visual record of production activities along the production phase.

The main idea is clearly to support the visualization of production status. As a result, near real-time on-site conditions can be accessed more flexibly in the digital SiteWalk environment. Notably, the 360°-imagery is time-marked, which allows users to navigate through and across various production stages and compare the as-built environments with each other and the as-designed BIM models. Figure 4.1 shows how such a comparison between the as-built and as-designed could look like in Dalux. This, for example, opens possibilities for progress monitoring, backtracking, schedule follow-ups, and identifying deviations. Furthermore, SiteWalk provides structured storage of site documentation and enables linking between images, registered issues, and model elements. Through these connections, the physical on-site conditions can be referenced in relation to digital project information.

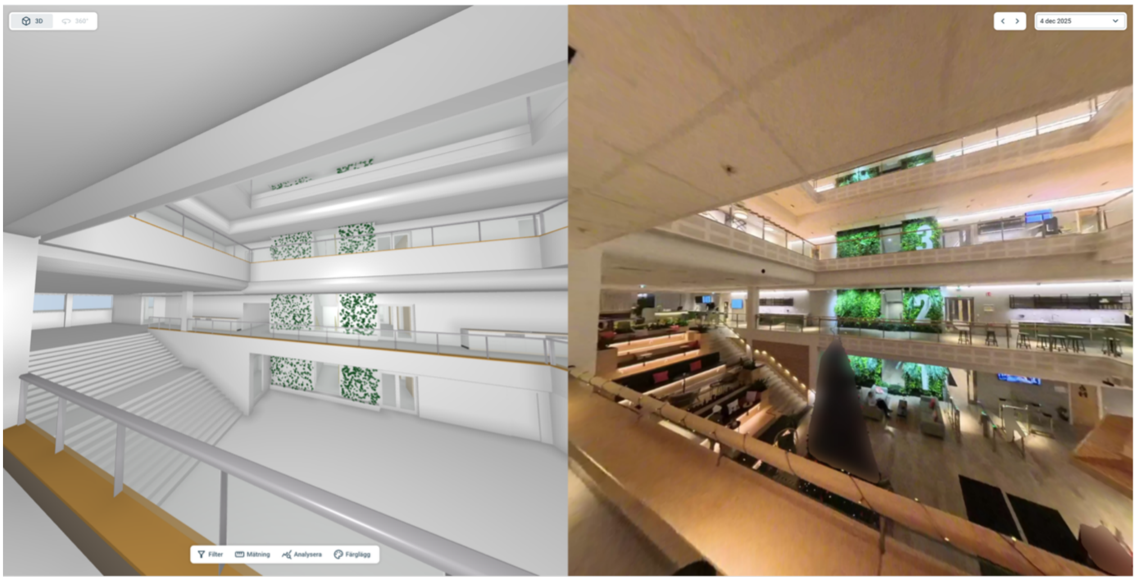

Figure 4.1: SiteWalk comparison of as-built and as-designed BIM model.

Furthermore, Figure 4.2 illustrates how the Sitewalk concept and its comparison capability enable the detection of deviations between the as-built and the as-designed environment. However, while detecting such deviations represents a key strength of the system, this comparison functionality can also support the development of record drawings and final as-built documentation.

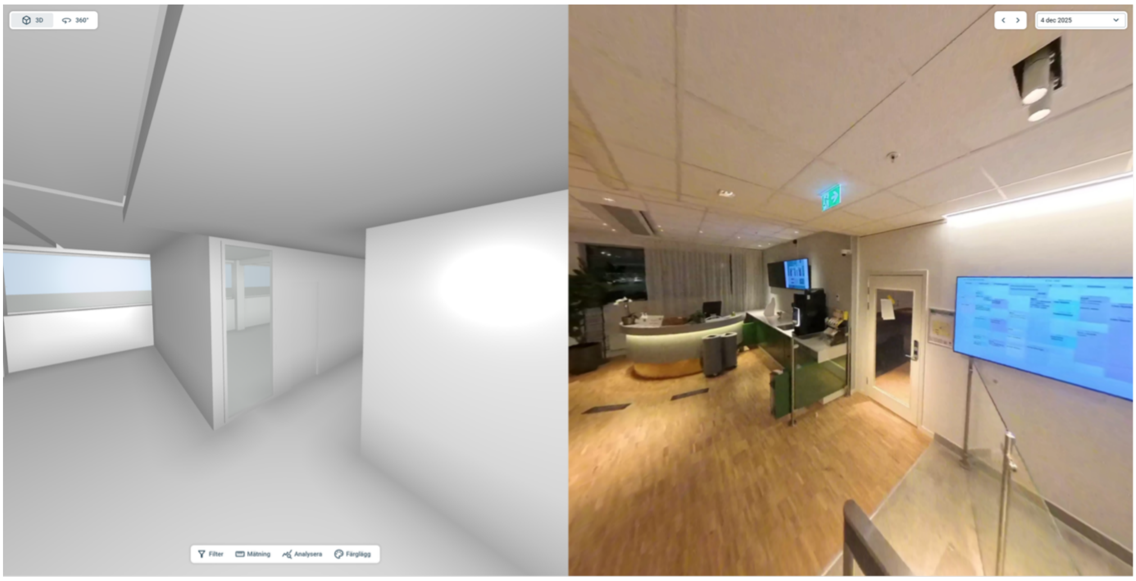

Figure 4.2: Side-by-side comparison illustrating that the built wall is shorter than indicated in the BIM model.

However, the exploration also revealed clear functional boundaries. While the concept enables easy and flexible access to on-site conditions, it is still dependent on manual interpretation. For example, it does not automatically identify construction elements or objects, it does not perform deviation detection autonomously, or analyze captured data to predict production risks. Lastly, the system does not automatically generate data-driven or predictive insights based on the visual documentation. Although the SiteWalk concept is valuable for documentation and improving transparency, interpretation of information, evaluation, and decision-making still relies on manual human assessment.

When recording and uploading SiteWalks to Dalux, both positive and negative aspects were noted. The initial thought was that the threshold for starting to utilize the concept was perceived to be low, with a simple and user-friendly interface. Further on, connecting the camera with the Dalux app was also straightforward.

However, some limitations were also noted. The first limitation is that, when moving between floors, the recorded SiteWalk must be transferred from the camera to Dalux before continuing on the next floor. This process takes approximately 2 to 10 minutes, depending on the size of the file. Although this may not seem like a big deal, it still means a few minutes of downtime on the construction site. The next upload phase, which processes and publishes the recording onto the Dalux project, takes much longer. During this process, people are blurred, which means that the more people that need to be blurred, the longer this process takes. To give some sense of time, an 8-minute recording takes approximately 5 hours to upload. However, in the real construction project visited for recording a SiteWalk to be used for the testing described in chapter 4.5, one floor required three 8-minute recordings to be fully covered. Thus, uploading such a recording often takes at least overnight.

Lastly, a clear limitation is the supported image quality in Dalux. Although the Dalux recommended camera, Insta360 X5, supports 8K and 120p, Dalux only supports 5.7K and 24p. Thus, the camera's full capacity could not be utilized.

4.2 Dalux user day and webinars

This chapter summarizes the observations and key takeaways from participating in the Dalux user day and relevant webinars.

4.2.1 Dalux SiteWalk webinar

The SiteWalk webinar introduced how the concept of SiteWalk works and its main functions. The three main functions, highlighted to constitute the core of the concept, included: navigating around the construction site, comparing 360°-images with BIM model, and comparing different 360°-images taken on various occasions. These functions, in turn, enable four key application areas that Dalux identified and highlighted as the primary objectives. These four application areas are progress, deviations, verification, and stakeholders, which are illustrated and further explained in Figure 4.3.

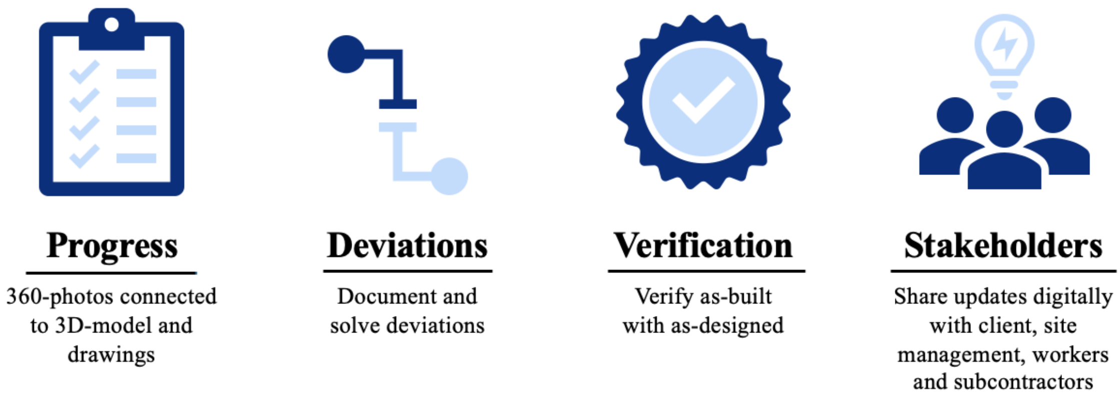

Figure 4.3: Main area of application of SiteWalk according to Dalux. The figure is adapted and translated from a Dalux SiteWalk webinar.

During the webinar, several benefits of using SiteWalk for the contractor were highlighted. These included enabling remote inspections, improving coordination, identifying objects and elements for reuse, enhancing communication with blue-collar workers and subcontractors, optimizing construction site planning, and supporting documentation of as-built drawings.

In addition to the contractor perspective, the webinar also pointed out the client and their operations as an important perspective that could benefit from implementing SiteWalk in their projects. The tool was presented to allow clients to digitally follow the execution phase in real time. Furthermore, it was described as useful for supporting wayfinding processes and serving as educational materials for businesses.

Although the webinar was relatively straightforward, it introduced interesting perspectives and ideas. Gaining insight into the software developers' vision and conceptual intentions of the concept contributed to a better understanding of SiteWalk, complementing the testing stage described in section 4.1. Moreover, the webinar provided valuable information and insights to prepare for the upcoming interviews with professionals who have experience using the SiteWalk concept in practice. This approach enabled to compare Dalux's intended use of the tool and its actual outcomes in real-world projects.

4.2.2 Dalux AI assistant webinar

During the “AI Assistant” webinar, Dalux presented how its current integration of AI mainly focused on the management of documents in Dalux Box. The AI assistant aimed to support tasks such as summarizing and reviewing files, including, for example, PDF documents, contracts, and safety documentation. In contrast to other third-party AI tools, however, Dalux's selling point for its AI assistant is that it runs and stores data internally in its own system and is not used for AI learning loops, which minimizes the risk of data exposure.

As it appears, the AI implementation within Dalux software development today seems to focus on improving efficiency in administrative tasks, such as document handling, rather than serving as a support tool for operational decision-making processes during project execution. Thus, the main takeaway from the webinar session is that AI applications moving beyond purely administrative tasks is motivated to be further explored.

4.2.3 Dalux user day Gothenburg

During the Dalux user day in Gothenburg, multiple presentations from Swedish construction companies were given, highlighting a wide range of Dalux applications and solutions in their daily work. Although none of these presentations were directly connected to the focus of this study, they provided insights into how the industry and users of the Dalux software played a central role in co-developing new functions. This approach aligns well with this thesis's focus on the user perspective for guiding technology development. After the presentation sessions, attendees had the opportunity to network, including with the Dalux team. At this point, contact was established with a member of the Dalux team, and the SiteWalk concept was discussed, both its current state and upcoming development. The conversation concluded with an exchange of contact information to arrange interviews with representatives from Dalux, who have significant insight into the SiteWalk concept.

4.3 Interviews

This chapter presents the findings from the conducted interviews thematically. The results both highlight current use of vision-based digital twin concepts as well as unexplored application areas and future potential.

4.3.1 Challenges in the execution phase

The conducted interviews disclose that the construction execution phase is affected and governed by several challenges that play a central role in why delays, cost overruns, and poor safety conditions are recurring problems in the construction industry. The interviewees highlighted challenges such as incomplete designs, tight timelines and schedules, fragmented workflows, and a long unaltered conservative culture as some examples of contributing factors. These challenges combined were described as creating a dynamic and complex environment in which deviations and inefficiencies are difficult to anticipate and manage proactively.

A constantly recurring problem that was pointed out across the interviews is that the construction execution phase is rarely initiated with a fully completed design. Instead, in many cases, the design process extends well into the execution phase.

> *"In a perfect world, design would be finished before we start building, but that's rarely the case." - (INT3)*

INT3 further explained that, as a result of this entailing gap between planning and construction, reactive adjustments during the execution phase are often required, which creates uncertainty and complexity in already tight time schedules.

This leads to another major challenge, which is partly connected to unfinished design and more strongly linked to pressured timelines.

> *"Most of these issues, which cause delays, cost overruns, and safety concerns, can be identified if you have the time to walk around, observe, and document properly. This lack of time not only affects larger deviations but also the accumulation of smaller, everyday issues that are often left unnoticed." - (INT1)*

As INT1 states in the quote, several problems that result in delays, cost overruns, and safety concerns can probably be identified earlier if more frequent and accurate observations are made. However, in order to do so, time is needed, which the often time-pressured construction sector rarely offers. Although major deviations, which are clearly classified as variation orders, are easy to note, INT1 means that smaller everyday issues risk going undiscovered and gradually accumulating over time.

When focusing more specifically on safety challenges, INT9 described them as stemming from a complex interaction involving organizational structures, human behavior, and the dynamic nature of construction sites. A key issue raised is that responsibility for safety and the working environment often rests with site or project managers, although larger projects might have clearly assigned roles that focus solely on these questions. However, more commonly, site and project managers, who must balance multiple priorities and therefore have limited time for proactive safety work, are responsible for this, INT9 explained.

> *"Many people often lack the maturity to realize they can hurt themselves until it actually happens." - (INT9)*

INT9 pointed out that construction sites often bring together people from various types of backgrounds, with different levels of experience, education, cultures, motivation, and awareness. The interviewee believed that this mix of individuals, combined with the fact that many are on site for only short periods, risks contributing to an inconsistent understanding of safety practices. Moreover, the interviewee also shared that even though many risks are familiar and recurring, the constantly changing conditions on site, like new work methods, environmental issues, and daily coordination between teams, can quickly make standard safety measures insufficient. As such, even well-known risks can lead to accidents if they are not regularly reviewed, INT9 stated.

Furthermore, the interviews underscore that good interaction and coordination between different disciplines are essential to enable smooth workflows for everyone.

> *"A challenge for us is that we are unable to work efficiently due to a lack of flow in both planning and execution, as we are heavily dependent on the progress of other disciplines." - (INT5)*

From a subcontractor perspective, INT5 expressed that they often experience a lack of flow in their planning and execution, because their progress is often strongly dependent on other disciplines. As a result, when facing deviations in the time schedule, it becomes difficult to determine blue-collar staffing needs, INT5 explained.

Lastly, the cultural aspects were identified as a threshold to tackle these challenges. As stated by INT4, people in the industry are used to working in a certain way and have a generally conservative attitude towards changes in their daily work routines. The interviewee added that narrow timelines and pressures to complete several tasks simultaneously result in limitations to the adoption of new approaches.

> *"It is largely about culture. People are used to working a certain way and think it works. We are always under pressure, sometimes it feels like everything is expected to be finished at the same time as we are building." - (INT4)*

4.3.2 Current use of Dalux SiteWalk

Throughout the interviews, the SiteWalk concept was repeatedly described and likened to the construction industry's equivalent of Google Maps Street View, most clearly stated by INT6.

> *"It is the construction site's equivalent to Google Maps" - (INT6)*

This explanation captured Dalux's primary interpretation of the SiteWalk concept and the core characteristics of how the tool is currently understood and applied among their clients and their construction projects today. This parable clearly reflects its function as a navigational and visual reference tool. The Dalux interviewees stated that, practically, this translates into the ability for everyone involved in a project to access site conditions and easily move between floors remotely. Thereby, it is possible to get an overview of current site conditions without physically being present and walking on site. As expressed by INT6, this provides managerial roles with greater flexibility, both in terms of where they can work from and how they allocate their time.

> *"It is a significant relief, I can now stay in the site office instead of having to run out and check things several times a day, because I can just look at the SiteWalk that was done yesterday" - (quote by a Dalux SiteWalk user, described by INT6)*

Furthermore, the interviews also revealed a clear practical benefit of this capability in terms of greater flexibility. By equipping both white and blue-collar workers with the possibility to navigate around the on-site environment digitally, the interviewees highlighted that it becomes easier and less time-consuming to address uncertainties and questions about site conditions that arise during meetings and discussions. Instead of needing to visit the site physically to verify details, SiteWalk allows such questions to be addressed directly, regardless of working location. For example, something as straightforward as confirming whether a hole has been drilled in a concrete wall can be checked and verified immediately. While it would be unrealistic to expect a supervisor or a site manager to keep track of every such detail, SiteWalk can help capture and document such events. Although keeping track of the progress of each hole being made is not of certain value for the responsible discipline, it might be for other disciplines, as explained by INT5 above, who often are dependent on other disciplines' work.

From the insights gained from the interviews, it can be established that Dalux SiteWalk is currently used primarily as a tool for documentation and visualization of construction site conditions. Thus, it largely plays a supportive role in practice and enables easy access to visual information rather than actively driving decision-making processes.

> *"It is mainly used for documentation and visualization... you can check what has been built without going out on site." - (INT1)*

From the main contractor's perspective, this is not an exception as described by INT1. At its core, it captures on-site conditions at regular intervals, giving the users a clear picture of what has been built without anyone needing to visit the site physically. INT1 also stated that this availability could be valuable when having project managers who are not continuously present on site, and thereby can communicate digitally.

> *"We mainly use it to see if other disciplines are finished so we can start and carry out our work." - (INT5)*

Additionally, the interview results show that the SiteWalk concept is also used to support coordination between disciplines. As stated by INT5, by allowing disciplines to navigate around the site environment digitally, it is possible to determine whether preceding work from other disciplines has been completed according to plan, and whether upcoming activities are possible to begin. In this way, INT5 explained that the tool can play an important role for short-term planning and coordination purposes, and to some extent replace regular communication.

As it is now, SiteWalk's main application is in the execution phase, primarily serving as a passive support tool for documentation and visualization. However, multiple interviewees claimed that visual documentation can also foster stakeholder communication within the project, such as the client, project managers, and designers. By offering a visual representation, stakeholders can better understand the state of the on-site conditions without having to be there physically.

4.3.2.1 Strengths of the SiteWalk concept

Among the interviews, several key strengths of the SiteWalk concept were identified and discussed. Most of these, however, were related to documentation, traceability, and accessibility of site information as expressed in the quotes below.

> *You could say it is a combination of documentation, history, and a really cheap insurance. - (INT7)*

> *"You never know when you will need documentation... but when you have it, it is extremely valuable." - (INT1)*

A recurring theme discussed in the interviews, highlighted as a key strength from both the main contractor and subcontractor perspectives, is the ability to create a continuous visual record of the construction process. The Dalux representatives, based on their clients' experiences and input, shared this picture, describing the concept as "a combination of documentation, history, and a really cheap insurance". INT7 further highlighted its value in providing evidence, traceability, and transparency of each discipline's construction process and progress over time. This perspective is further strengthened by INT1, who emphasized that the value of such documentation might not be recognized immediately and that SiteWalk can be seen as a proactive measure to make potentially necessary information accessible. Providing a foundation for motivating additional payments due to variation orders and additional work was a concrete example, brought up by both INT1 and 9, of how this type of documentation could be used.

> *"It is kind of like a time machine... You can go back and see exactly what and how things were done" - (INT6)*

Furthermore, several interviewees highlighted the time dimension of SiteWalk, which allows users to travel back and forth in time on the construction site. As INT6 noted, the tool can, thereby, be described as "kind of like a time machine" that lets users review work being carried out in earlier stages in retrospect.

Another important strength that was highlighted across almost all interviews is the ability to communicate and share information about the site environments with stakeholders who are not physically present on site. As an example, INT3 pointed out that SiteWalk can be used to illustrate progress and as-built conditions to designers, clients, and other actors, while INT1 noted that many project managers are not on site regularly.

> *"It makes it possible to illustrate and show the progress to, for example, the designers, clients, or other stakeholders in the project who cannot be on site daily." - (INT3)*

> *"There are many project managers who are not on site very often." - (INT1)*

In either of these contexts, several interviewees claimed that the tool can contribute to improved situational awareness by offering an easily accessible, clear, and up-to-date understanding of site conditions, regardless of the physical presence of the stakeholders or not. As stated by INT6, such capability enables greater flexibility in how project stakeholders can engage with their projects, both in regard to working remotely and having faster access to relevant information.

In addition to its role as acting as a documentation and communication support tool, INT8 also emphasized that visual site data can provide more systematic site supervision and quality control. Having a continuous flow of visual site data can supply continuous monitoring over relevant areas, which supports a more consistent approach to inspection of the construction site, the interviewee stated. Further on, INT8 highlighted that the ability to directly connect issues, as well as comments, at designated locations in the visual documentation can amplify traceability and follow-up processes. This gives acknowledgment of what, when, and where the inspection was conducted, which, in turn, enhances the quality assurance and related documentation, the interviewee claimed.

To summarize, the findings suggest that the main benefits and strengths of the

SiteWalk concept at present lie in its ability to easily capture reality, document and preserve information over time, and make it accessible to a wide range of stakeholders regardless of their location. Meanwhile, the findings from the users seem to align with the Dalux representatives' vision of simplicity and minimal threshold being central pieces in making the SiteWalk concept appreciated among their customers.

4.3.2.2 Limitations of the SiteWalk concept

Despite the strengths of the SiteWalk concept, the interviewees disclosed several limitations that can be divided into three different areas: collection of data, technical restrictions, and adoption.

One major limitation concerns the data collection, which is related to the time commitment needed and the fact that it must be performed manually. INT2, who was responsible for updating the project's SiteWalk once a week, noted that a full SiteWalk route requires a considerable allocation of time, corresponding 1.5 to 2 hours to cover the 12'000 square meter construction site. Meanwhile, INT4 emphasizes that the recording process could probably be automated since the routes are repetitive.

> *"It takes quite some time to walk and record everything." - (INT2)*

> *"The recording process is time-consuming... a robot could definitely do that to save time." - (INT4)*

Further on, technical limitations were seen as a threshold, especially related to image quality and the environment's condition. INT6 stated that there are restrictions in the resolution, while INT4 revealed that the footage is sensitive to lightning conditions, where it can be neither too dark nor too bright. These findings are also aligned with the authors' findings when recording their own SiteWalks.

> *"There is a limitation regarding the resolution and the image quality." - (INT6)*

> *"Sufficient light is a recurring limitation. It can not be too dark, but at the same time the images can be overexposed if it is too sunny and light." - (INT4)*

Furthermore, the adoption and integration of the concept in project workflows was discussed. INT1 explained that SiteWalk is not yet a standardized approach to work. At present, SiteWalk is not pushed to be a standard practice and is not embedded as a collaborative way of working across projects. Instead, adoption depends on initiatives on an individual level and perceived value from project to project. Additionally, in practice, it is up to each and every discipline to decide whether they find it useful or not for their daily work.

> *"It has not really been pushed as a standard way of working." - (INT1)*

Interestingly, INT8 explained that they have moved away from using SiteWalk and nowadays use regular 360°-images in Dalux. The reason behind this was to enable better control of the location where the photos were taken. The interviewee claimed that taking single 360°-images enabled better comparison between the occasions since it allows to carefully choose the exact same location of the image every time. Although following the same route when recording a Sitewalk, the selected images vary slightly each time, which was seen as a considerable limitation.

Lastly, INT6 highlighted that the main limitation might lie in the users' imagination. Thus, the interviewee claimed that the outcome is largely determined by the individual's engagement. Although the main application is for documentation and visualization, clients come up with new ideas at regular intervals on the value the concept can bring.

> *"In the end, it is only the user's imagination that limits the value you get from it." - (INT6)*

4.3.3 Current use of AI in practice

According to the conducted interviews, the current state of using AI in construction is still limited. The primary use has been for administrative tasks instead of production activities. In general, the interviewees admitted that the maturity level of AI use is low and not broadly integrated into either daily workflows at the site or to support decision-making.

In several interviews, it was emphasized that AI is mostly used for low-stakes and time-saving tasks. INT1 highlighted that the use of AI is primarily for summarizing documents and invoices, while INT3 underscored that it is more of a supportive tool for administrative purposes and is not applied in the dynamic production on-site.

> *"I mostly use it to summarize documents or invoices." - (INT1)*

> *"It is more of a support tool for administrative tasks... not something we use in the actual production work." - (INT3)*

Meanwhile, one interviewee revealed that an increasing acceptance and familiarity with AI tools has been experienced. INT5 emphasized that AI tools such as Copilot are being used for navigation in comprehensive technical documents to be more efficient. The interviewee added that AI is used by people of varying ages and backgrounds within their team. However, from the interviews, it can be derived that the implementation of AI towards production-related activities remains limited. Several interviewees also highlighted a clear potential for a broader use of AI, but added that there is uncertainty regarding the applicability of how and where AI can be applied, particularly related to execution.

> *"I use it more and more. I even have a 60+ year old colleague who uses it. We use Copilot to find information in large documents, for example, technical descriptions. Currently, AI is mainly used for administrative works, however, there is definitely potential within other areas, but it is hard to know exactly where and how." - (INT5)*

Besides the uncertainty, the interviews underscored practical and organizational obstacles. INT4 explained that the confidentiality constraints limit the use of AI tools in certain projects, despite interest in using them.

> *"I am involved in a project where I would like to use AI, but we are not allowed to since the project is confidential." - (INT4)*

However, in contrast to the other interviewees, INT10 described a more advanced use of AI that was much more integrated into the daily workflow as a standard practice. For example, the interviewee used AI to analyze differences between building types that were significant during the tendering process. In addition, AI allowed the interviewee to easily search for and extract insights from internal databases, for example, to evaluate different methods and material choices from previous projects.

Altogether, the interviews suggest that AI's current state is in the early stages of adoption. The interviews demonstrate that AI use clearly varies between roles, with production-related roles generally using AI less than office roles, such as cost estimation and planning. Simultaneously, there is an awareness of the potential of AI, but the concrete field of application related to the execution phase is still undiscovered.

4.3.4 Progress and cost control in construction projects

Since delays and cost overruns represent a central part of the problem statement, the interviews also aimed to address and capture perspectives related to progress and cost control during the construction phase. During the interviews, several interviewees described that project control largely relies on recurring forecasts and follow-up procedures. In these, planned progress is continuously compared against actual project outcomes. The interviewees explained that the forecasts are built on a foundation of material consumption and ordered quantities, remaining labor hours, and alignment with the project schedule.

Although the interviews indicate clear and structured routines, the relation between progress at the site and reported figures is not always as desired. INT9 explained that financial follow-ups are closely connected to assessments of production progress on site. However, the interviewee emphasized that these assessments are rarely based on exact measurements. Instead, it is most often built on experience-based estimations and assumptions in terms of how much work is completed. In regard to this, the interviewee highlighted it is a "significant risk" that the actual work on site does not match the progress reports. According to INT9, this risks creating uncertainty in progress and cost forecasting and decision-making processes, especially when deviations are identified late in the project stage.

INT9 further claimed that even though they are generally confident with their own forecasts and cost estimations, they still heavily depend on the ability of project participants and subcontractors to evaluate ongoing production and estimate outcomes. This was described as particularly challenging in large and complex projects, involving multiple subcontractors. The interviewee highlighted that uncertainty may arise in subcontractors' forecasting practices. In this context, INT9 explained that it is more common for there to be a gap between the forecasts received and current site conditions compared to schedules. For example, the interviewee described situations where subcontractors had already consumed way more labor hours than initially planned, but despite this, still maintained unchanged cost and progress forecasts. According to the interviewee, this was seen as a warning sign that the reported forecasts were not aligned with the actual production status on site. Whether this was due to a lack of awareness of site conditions or the subcontractors having the belief to be able to catch up, the interviewee left unsaid.

Furthermore, INT10 described that visual documentation of the site could potentially be used to support cost calculations and decision-making during production, particularly when calculating variation orders and change requests. Having a visual record accessible of on-site conditions provides a more reliable basis for assessing the scope and impact of changes requested by the client, the interviewee claimed.

4.3.5 Future potential and extended use of vision-based digital twin concepts

The future potential and extended use of DTs can be linked with a recurring topic in the interviews. There is a demand for automated progress tracking, thereby merging the progress with the time plan and cost control. Particularly, INT5 stated that there is a huge value in being available to review the status of what has been built. Especially, in some projects where there are requirements to show that the work has been completed before invoicing is allowed. The value of syncing the schedule and budget with a quantified number of remaining labor will streamline the allocation of work, which currently has evaluation difficulties.

> *"In some projects, you are not allowed to invoice until the work has been completed. In those cases, it would be valuable to be able to clearly show progress and what has actually been done. It would help track how much work remains and how that compares to the remaining budget and schedule. That, in turn, would support decisions on staffing, which is otherwise difficult to estimate. If the entire follow-up routing, or at least the basis for progress reviews, could be automated, it would be highly valuable." - (INT5)*

Further on, it also became evident that, although SiteWalk and 360°-imagery are collected during the execution phase, they can serve as a valuable tool beyond production. For example, INT10 identified several potential applications in tendering processes. The interviewee highlighted that vision-based site data could support knowledge transfer between projects. If the construction processes and site conditions are documented systematically, the gathered data opens up possibilities for project teams to revisit previous projects and to refine cost estimation inputs for similar projects in the future, the interviewee stated. Thus, INT10 means that the visual documentation, which serves as the main strength and use of SiteWalk during execution today, could potentially be valuable in the long term as a resource for organizational and cross-project learning.

Furthermore, during the interviews, it was also mentioned that visual documentation could be particularly relevant and useful in refurbishment and reconstruction projects. INT10 mentioned that even though drawings and 3D models of the current building and its systems exist, it is common that the as-built state differs, which creates an uncertainty regarding existing conditions.

From a cost estimation and tendering perspective, INT10 then highlighted two distinct use cases. Firstly, the interviewee claimed that SiteWalk, or corresponding 360°-imagery visualization, could be useful for the tendering phase. Conducting a site capture before the tendering process would provide a comprehensive understanding of the existing environment, which can be accessed digitally at any time. This would enable estimators to better grasp and anticipate the scope of work and thereby deliver better accuracy in their tender calculations, the interviewee stated. Secondly, INT10 means that if there is 360°-image documentation available when entering refurbishment projects, it can help reduce uncertainties related to deviations between drawings and actual site conditions. This was highlighted by INT10 as an issue for tendering work in refurbishment and rebuilding projects. More specifically, the interviewee described that access to visual records can show hidden installations, such as pipes behind walls or above ceilings, which would be valuable to both improve the reliability of cost estimates and reduce the risk of unforeseen conditions. INT10 described that such 360°-documentation could help minimize the need for assumptions or extensive inspections during the tendering phase, which could save time.

In addition to the above described future potentials, INT7 also highlighted the potential value of SiteWalk in projects involving inventory reconstruction and refurbishment. The Dalux representative noted that their customers have started to raise questions related to this type of application, which indicates a growing interest in using SiteWalk to support inventory and reuse-oriented workflows. As an example, INT7 described how the ability to digitally navigate the site and document observations could be used to inventory existing components and identify elements with reuse potential before the reconstruction starts.

4.3.6 Key takeaway from the interviews

If summarizing all the interview findings into one common takeaway, it is relieved that there is a clear gap between the current state of construction project practices and the potential in using visual site data and AI. Although there are strong capabilities, the practical implementation remains limited. The interviewees considered that this gap is not solely related to technical or organizational limitations, but also how well the tools align with their existing workflow and the users' actual needs. Across the interviews, there was a recurring theme, but especially emphasized by INT6. The interviewee stated that to achieve a successful adoption, there is a need for low implementation thresholds, simplicity, and a strong focus on usability.

> *"What people use has to be simple, as simple as possible. That is when people will actually use it. It should not be more than a few clicks away."*
> *- INT6*

4.4 Workshop with a subcontractor with no prior experience of Dalux SiteWalk

To complement the insights gained from the interviews, a workshop with a more open-ended discussion was conducted. This provided an additional subcontractor perspective while enabling an exploratory and forward-looking approach. While the interviews were grounded in examining the current use and application of SiteWalk, the workshop format allowed for a broader and more future-oriented discussion, thanks to the participants' lack of prior experience with similar concepts. Thus, the focus of the workshop was to explore how visual data could support existing workflows and practices.

4.4.1 Bridging design and on-site reality

A central theme highlighted during the discussion was the deviation between the design and the actual conditions on the construction sites. The participants described that reality often differs slightly from drawings and models, which, according to them, may lead to installation clashes, missing details, and production-related constraints not being fully captured. One contributing factor identified by the participants was that designers are rarely present on site, which they argued can result in a limited understanding of how installations are carried out in practice. This perceived gap in understanding was described as potentially leading to solutions that are less adapted for efficient installation. Examples raised included insufficient consideration of hanger systems and design solutions that are optimal from a theoretical perspective but difficult to handle in production, such as unnecessarily large pipe dimensions. Overall, the participants suggested that this misalignment risk results in inefficiencies during the execution phase that could have been avoided.

In this context, the participants described visual site data, such as 360°-images, as a potential means to improve communication between production and design. It was suggested that visual feedback from the construction site could enhance designers' understanding of actual site conditions. According to the participants, this could contribute to more production-friendly solutions. Furthermore, 360°-images were highlighted as a promising basis for producing as-built drawings, as they were perceived to enable a clearer visual capture of the actual execution and thereby improve traceability in later project stages.

4.4.2 Support for project management and planning

Another theme raised during the discussion was the potential to use visual site data to support project and site management and planning. The participants noted that 360°-images could, in addition to being used to follow up on project progress, also support the planning of upcoming work activities and the coordination of resources among different actors. This is in line with the current use described by INT5, who used SiteWalk to follow up on other disciplines' work to plan their own. In particular, the ability to "travel back in time" and visually compare different stages of production was perceived as valuable by the participants, as it would enable them to get a clearer overview of how work progresses over time.

Furthermore, the participants highlighted that this type of visual information could contribute to an improved basis for decision-making by providing a concrete picture of current on-site conditions. The ability to quickly gain an understanding of what has been completed and what remains was described as supportive in the participants' daily work, particularly in projects where multiple activities are ongoing in parallel.

4.4.3 Cost control and contractual processes

Moreover, the workshop discussion also covered the potential of using visual site data as support for project progress and cost tracking, as well as contractual processes. The participants noted that 360°-images could serve as a basis for documenting and verifying executed work, particularly in relation to the handling of variation orders. If being able to visually link specific work activities with specific times and locations on site, the participants considered it possible to create a clearer picture of what has actually been carried out and when.

In addition, the participants highlighted that this type of visual documentation could contribute to improved transparency between project stakeholders as it creates a common reference point. Having the ability to revisit and review earlier stages of production was described by the participants as particularly valuable in situations where uncertainties and disputes arise regarding performed work or cost allocation.

4.4.4 Remote project management

During the workshop, visual data from the construction site was also discussed as remote project management support. The participants described that this could enable remote access to near real-time on-site conditions, which could make it easier to stay updated and gain an understanding of current project status, and thereby reduce the need for physical site visits. This was considered to contribute to increased time efficiency and flexibility, while also enabling project management activities to be done remotely, for example, coordination and follow-up work. In addition, the participants highlighted that this flexibility may be particularly relevant in geographically dispersed projects or for project management roles that are not present on the construction site on a daily basis.

The participants further emphasized that visual documentation can be particularly valuable in practice when handling problems and resolving conflicts. Lastly, although the participants expressed a generally positive view of the flexibility enabled by visual documentation, they also emphasized the importance of physical presence on-site. It was clearly stated that site visits are still necessary to verify details and gain a spatial understanding of the environment, while also maintaining oversight from a safety perspective, which is further discussed in Section 4.4.6.

4.4.5 Limitations and practical constraints

The workshop discussion also underscored a few potential limitations and practical challenges associated with using visual site data. Although participants generally found the 360°-image quality in Dalux SiteWalk sufficient for an overall understanding of the construction site, it was considered insufficient for examining details. Participants saw this as particularly relevant in situations requiring more precise evaluations, for example, when checking smaller installations or specific execution and installation details.

Furthermore, participants emphasized that usability could be more limited in larger, more complex environments, especially industrial projects with high ceilings, such as a warehouse. In such a project, the distance between the 360°-images and the installations on the roof increases, making it difficult to distinguish details in the images, one participant stated. As a potential solution to this problem, the same participant highlighted the proposal to allow higher image quality in certain files when needed, since the camera equipment has a higher capacity than what is currently supported and allowed in Dalux. In this context, the need for additional documentation, such as detailed images, was pinpointed to ensure a sufficient level of information.

4.4.6 Potential negative on-site safety implications

Further on, a risk was identified during a discussion in the workshop that is related to tools like SiteWalk. Tools such as SiteWalk offer project managers the possibility to work more remotely. Especially, one participant meant that the physical need of being present for the project manager, in a sense, may vanish. The contributor added that the safety perspective is in a state of crisis when management personnel are not present. It was also prominent that frequent as well as unexpected presence on site is crucial for maintaining a safe working environment. In addition to the potential concern of management personnel's non-presence on site and being replaced by digital monitoring, it may become more predictable when inspection occurs, which could lead to work sometimes being performed without the same level of supervision. Lastly, the person in question expressed that digital tools should be considered as a supplement and not a substitute for the actual presence on-site.

4.4.7 Future potential

Lastly, the workshop came to the conclusion that there is a certain amount of future prospects. The participants explained that the SiteWalk concept could, in the future, be adapted for a more comprehensive knowledge development within company organizations. Especially, the potential in compiling different projects' related data was highlighted. One participant filled in with that, for instance, technical documents, standards, and solutions from previous projects into an internal system for the company.

This led the dialogue into a further discussion about the possibility of integrating AI-based solutions. The contributors stated that, by collecting post-project review data, project managers can gain better insights and address design-related questions more effectively. Lastly, one contributor concluded the workshop by gathering data could act as a "bank" to make accumulated knowledge more accessible and applicable in ongoing projects.

4.5 Safety risk detection on construction sites using AI and 360°-image SiteWalk data

The interview results demonstrated that the current use of AI within the construction sector is limited, particularly in relation to production-related activities. Meanwhile, several interviewees highlighted the potential of combining AI with visual site data, such as 360°-imagery from Dalux SiteWalk, to improve safety conditions and the working environment on construction sites.

To further investigate the identified potential, a practical test was conducted in which AI was used to analyze visual site data with the aim of identifying safety hazards. The tests followed the same methodology as described in Yakupogullari et al. (2026). The AI analysis was run twice, the second time with refined vocabulary. The results of the tests are presented in Figure 4.4. A description of the three result categories is given below:

- Positive: Correctly identified the hazard without hallucinations.
- Overshot Positive: Identified the hazard but included false assumptions or hallucinations.
- Negative: Failed to identify the hazard

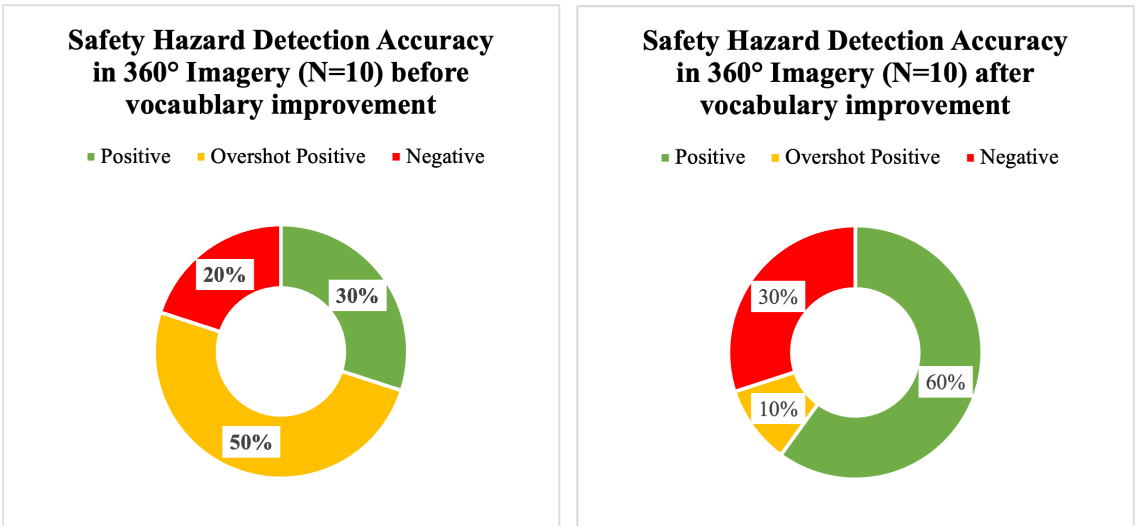

Figure 4.4: The test results before and after introducing complex nouns, relevant to the construction site environment captured in the images, to the AI prompts.

As illustrated in Figure 4.4, the AI model GEMMS framework correctly identified 30% of the safety hazards, while 50% were classified as overshot positives and 20% were not identified in the first run. This result shows that AI tends to over-identify potential risks rather than overlook them. However, when introducing complex nouns relevant to the captured construction site environment, the share of positive AI-generated outputs increased significantly. Examples of what a positive, overshot positive, and negative output could look like are given in Appendix Chapter 2, Figure B.1-B.3.

5

Discussion and analysis

5.1 From visual support tool to project management value

The collected results from the different methodological approaches indicate that the primary value of visual site data lies in its ability to improve information accessibility, situational awareness, coordination, and traceability during the construction execution phase. In this study, SiteWalk has been used as an empirical example to illustrate how 360° image-based site documentation can be collected and used in practice. The focus has not been on evaluating the specific software, but rather on investigating how visual site documentation can contribute to project management during the execution phase of construction projects.

This perspective aligns with the literature concerning vision-based DTs in relation to project management practices. Previous studies describe 360°-image technologies and other vision-based tools as approaches to capture site conditions, monitoring production status, and supporting decision-making during project execution (Pal et al., 2023; Shinde et al., 2023; Yang et al., 2024). Simultaneously, the empirical findings of this study indicate that improved access to visual information can strengthen project monitoring, coordination, and communication between project actors. This is particularly in line with the measurement and uncertainty domains presented in Project Management Institute (2021), which emphasize the importance of monitoring project status, structuring information, and managing deviations to support effective decision-making.

Furthermore, the relationship between decision timing and project performance becomes relevant in this context. Earlier access to reliable information increases the possibility of identifying risks and acting before deviations develop into delays or cost overruns (Ilozor & Kelly, 2012; MacLeamy, 2004). As such, visual site documentation can be seen as a mechanism for improving informational accessibility, situational awareness, and enabling proactive project management during project execution.

In relation to the literature on DTs, 360° image-based site documentation can be understood as a low-maturity level vision-based DT. Sacks et al. (2020) describe DTs as continuously updated digital representations that reflect physical and functional characteristics of a system. Meanwhile, Yang et al. (2025) explain DT maturity as a level-based development from basic digital representations towards more advanced and autonomous systems. By combining these perceptions, visual site documentation can be seen as an initial step within a broader implementation journey toward more advanced DT environments. As of now, the technology provides a visual and time-bound representation of the construction site, but lacks automated interpretation, predictive functions, and independent feedback loops.

This interpretation is strongly supported by the empirical findings, which reveal that human interpretation remains crucial in order to identify deviation, assess production status and progress, and transform visual information into actionable decisions. Thus, the current value lies in improving transparency, traceability, and accessibility of project information. This, in turn, highlights a general finding: although visual site data increases the availability of project information, it is still dependent on human interpretation and contextual understanding. Thus, the technology currently supports managerial decision-making rather than replacing it.

Furthermore, one of the clearest practical values identified in the findings is that visual site data can improve situational awareness within construction projects. Giving access to the construction site digitally enables project stakeholders to review project status without being physically present on site. This was reinforced throughout both the interviews and the workshop discussions. The participants explained how remote access to visual site data can reduce the need for unnecessary physical site visits, while also improving follow-up, coordination, and communication between actors. This finding suggests that the managerial value of visual documentation is closely related to improved informational accessibility.

This can be further connected to the measurement and uncertainty domains in PMBOK, emphasizing that effective project execution depends on continuous access to updated and structured project information to support decision-making (Project Management Institute, 2021). In this context, visual site data can help reduce information asymmetry between actors and more up-to-date awareness of the construction site. Instead of relying on verbal descriptions, stakeholders get a shared situational reference point. As a result, the technology can contribute to more aligned decision-making processes and improved coordination between the involved actors.

Moreover, the results show that the perceived value and suitability of visual site documentation vary depending on project size and complexity. In general, the findings indicate that larger and more complex projects appear to be more suitable and provide the greatest potential value. Additionally, several interviewees explained that visual site data could support follow-up of preceding disciplines and determine whether subsequent work could begin according to plan. This finding can also be connected to broader literature on project management concerning project dependencies and coordination complexity. As explained in the literature, construction projects are characterized by continuous interactions between stakeholders, resources, schedules, and ongoing activities. When such dependencies are not coordinated effectively, even small disruptions or information gaps risk leading to significant consequences in terms of delays and increased costs (Lafhaj et al., 2024; Purushothaman et al., 2024). However, the findings also indicate that the potential values become less obvious in smaller and less complex projects. In such projects, the required effort for continuous data collection may be more difficult to justify, considering the expected benefits.

As mentioned, visual site documentation becomes particularly useful in projects where subsequent work is interdependent. The results from the interviews and workshop show that it can be utilized to review whether previous disciplines have completed their work. Thus, visual data can provide practical support for coordination between project actors, which also connects to the literature. The literature suggests that delays and cost overruns occur in the execution phase because of poor planning, ineffective site management, weak communication, and late decisions (Gómez-Cabrera et al., 2024; Tafesse, 2021; Purushothaman et al., 2024). By sharing a similar visual basis, the dependencies on verbal reconciliations and subjective interpretations can be reduced, and coordination can be improved.

Another considerable finding is that visual documentation can also enhance traceability in projects. Documenting the construction site continuously opens up the possibility to review previous site conditions, which can support follow-up procedures, quality assurance, handling of variation orders, and contractual disputes. The literature emphasizes that vision-based DTs can contribute with contextual and appearance-based information. It can be difficult to capture the workplace organization, ongoing activities, and the observable production conditions solely in geometric models (Koulalis et al., 2022; Pal et al., 2023; Shinde et al., 2023). This suggests that visual documentation can bridge the gap between traditional drawings, BIM models, and the practical reality at a certain point in time.

Furthermore, renovation and refurbishment projects, where uncertainty considering existing conditions is often higher, also appeared as potential relevant areas of use. Several interviewees and participants in the workshop session explained that drawings and BIM models do not always correspond to the as-built conditions. Thereby, visual site documentation can foster support for planning, coordination, and decision-making by providing more reliable insight into the physical state. The findings also suggest that 360°-image documentation may reduce the need for assumptions and repeated site inspections while also improving the reliability of cost estimates and reducing the risk of unforeseen conditions. This observation is in line with the DT literature concerning life cycle perspectives. Previous research emphasizes that as-built is not only relevant during the execution phase, but also for future operation, management, adaptation, and renovation processes (Sacks et al., 2020; Opoku et al., 2021; Reja et al., 2024). This suggests that buildings that are likely to change over their life cycle can particularly benefit from visual documentation from the beginning of construction. In this manner, the value of visual data clearly extends beyond the execution phase and may continue to generate value throughout the building's life cycle, although the documentation is made during execution.

Furthermore, an area with application potential is the correlation between production, progress monitoring, and cost control. The results indicate that occasionally there is a gap between as-built and the project's reporting, forecasts, and financial monitoring. In these occasions, visual documentation can act as a validation for project management. This is also in accordance with the literature. DTs can support progress monitoring, time planning, and cost control during the execution phase through comparisons between updated site information from the construction site with schedules, BIM models, and cost bases. Simultaneously, the literature underscores that to benefit from visual data, it is dependent on data quality, regular updates, and clear working methods for how the information should be collected and used in decision-making processes (Reja et al., 2024; Yang et al., 2024).

Importantly, in order to assess the actual value creation of visual site data, it is necessary to place the concept in an economic context. This cost perspective is important since the literature indicates that vision-based DTs are more scalable, allow for higher update rates, lower data acquisition costs, and are less resource-intensive than LiDAR- and laser-scanned approaches (Pal et al., 2023; Yang et al., 2024; Zhou et al., 2025). Since this study evaluates the Dalux SiteWalk concept as an example, Dalux was contacted in an attempt to obtain indicative pricing information. However, it turned out Dalux could not provide any price-related information.

The only available indication regarding the software cost is from a Peab employee, who stated that the Dalux Field Pro package, which is required to access the SiteWalk functionality, increases their standard Dalux subscription cost by approximately 25%. However, since the cost of the base subscription remains unknown, the actual financial impact is difficult to quantify. Although the additional subscription cost does not appear to be perceived as excessively significant, there has been no active effort to promote or communicate that the tool is available to subcontractors in the project in which INT1 is involved.

Nevertheless, it is possible to discuss the potential time saving. As explained by INT2, producing a SiteWalk recording for the specific project of 15,000 square meters takes approximately 1.5 to 2 hours. The same project involves between 15 and 20 white-collar workers and between 100 and 150 blue-collar workers, according to INT9. Then, the relevant question becomes whether the total time saving of having SiteWalk available among these workers exceeds the 2 hours it takes to produce the recording or not.

Simultaneously, the economic value depends on how actively the visual site data is used and in what type of project it is implemented. In large and complex projects, where many white-collar workers and construction workers depend on updated information about the site, even small time savings per person can contribute to a larger project value. To put this into context, a SiteWalk recording for INT2, covering 15,000 square meters, took around two hours to complete. This means that the recording time would already be compensated for if each of the 20 white-collar workers in the projects could save ten minutes a week by, for example, verifying a detail remotely in SiteWalk and thereby avoiding a physical site visit. This corresponds to a total of 200 minutes of saved working time, which exceeds the time required to make the recording. This shows that already minor use would justify the effort of making a recording, although the subscription required is not considered here. However, in smaller and less complex projects, the equivalent documentation may be difficult to motivate since there are fewer project actors involved, and the need to continuously check and share information about the status of the site is not necessarily as extensive. Thus, visual site data should not be considered as a naturally value-creating tool itself, but as a support tool whose value depends on what sort of project it is applied to and how the data can be integrated and used in the project management processes.

5.2 Barriers to value creation: technical limitations, workflow integration, and adoption

An interesting finding from the interviews is that the limitations of the SiteWalk concept, in this case, are not necessarily directly related to its technical capabilities. Instead, the limitations are rather about how well it is utilized and integrated in practice. The interview results show that the users themselves define and set the functional boundaries of the system by deciding whether to use it as a passive documentation and visualization tool or actively working on integrating it into project management processes such as progress tracking, quality control, and cost monitoring. Currently, SiteWalk is largely perceived as a supplementary or "nice to have" tool rather than as a critical and value-generating component of project management workflows, which clearly limits its practical impact despite its potential. This highlights the users' role in shaping tomorrow's workflows and the sector's digitization journey for the future. The users' central role, in turn, places importance on simplicity and user-friendly tools with low adoption thresholds, which was highlighted as fundamental across the interviews.

One of the clearest practical barriers identified both during the interviews and exploration of the SiteWalk concept was the dependency of manual data collection, both in terms of recording, as well as interpreting the visual site data when published. Although the threshold for recording SiteWalk was perceived to be low and user-friendly, the process still requires dedicated time and effort from site personnel. Regular rounds must be performed manually, and the recordings must be processed and uploaded before becoming accessible on the platform. Meanwhile, the tool's value is largely dependent on users continuously prioritizing the documentation process within already time-pressured project environments. Several interviewees explained how time constraints already limit proactive monitoring and follow-up activities on site. Under such conditions, continuously updated visual documentation risks being deprioritized if the generated value is not perceived to be high enough.

This, in turn, reveals a fundamental dependency between the usefulness of visual site data and update frequency. A vision-based DT only mirrors reality if the gathered data represents the production's actual status. In dynamic construction environments where conditions change on a daily basis, irregular and too low update frequencies lead to decreased reliability and relevance of the tool for acting as decision support. This means that recurring and frequent updates are needed to scale up its usefulness from documentation and visualization. Thus, the practical value and usefulness are not created solely by the technology existing, but by maintaining a consistent and updated flow of data over time. This, in turn, aligns with the literature emphasizing that execution-phase DTs require continuous updating procedures to remain useful in a dynamic construction environment (Reja et al., 2024; Yang et al., 2024).

In addition to workflow-related barriers, the findings also highlight several technical limitations connected to the system's visual capabilities. Since concepts like SiteWalk rely on image-based data capture, the quality of these images is dependent on environmental conditions such as lighting, camera positioning and angles, and distance to the objects being documented. Both the workshop participants and interviewees highlighted that the image quality in some cases risks being insufficient for reviewing smaller details, particularly in industry environments with high ceilings or limited lighting conditions. This indicates that the usefulness is not only limited by the software's functionality, but also by how well the data collection works out in varying, real construction environments. Similar limitations were identified in the literature, where vision-based DTs are described as sensitive to environmental conditions, which potentially can have a negative effect on interpretation accuracy and CV performance.

Connected to the image quality, the exploration of the SiteWalk concept revealed that processing and compression limitations can negatively affect the usefulness of the tool. Although modern 360°-cameras support high image quality, the recorded material is compressed when uploaded to Dalux and is limited to lower resolutions than what the Insta360 X5 camera supports. Meanwhile, higher image quality is likely to result in longer processing and uploading times. This creates a conflict between activities requiring high image quality, such as quality checks or status assessments, and the strength of high update frequency and visualizing as close to real-time environments as possible. A potential solution to this conflict would be to enable a function that allows users to temporarily select specific files or images for higher resolution, as proposed by one of the workshop participants.

Another important barrier raised in both the literature and empirical findings is the lack of implementation in standardized workflows and organizational integration. At present, SiteWalk is inconsistently used across Peab's projects and, instead, largely depends on initiatives from individuals rather than company-wide adoption. Several of the interviewees described that the tool is not yet embedded into standardized project management routines. This creates a situation where inconsistent utilization and dependency on certain individuals hinder the full potential from being achieved. Similar implementation barriers are described in the literature, where Yang et al.

(2025) argue that DT concepts in construction remain at low maturity levels because they are not integrated into traditional workflows and lack standardized implementation principles.

The results also indicate that adoption barriers are closely connected to the construction industry's known conservative culture. Several interviewees indicated, but most clearly stated by INT4, that there is generally a resistance to changing established working routines, particularly in production environments that are characterized by time pressure and fragmented coordination between disciplines. In such situations, even simple and user-friendly tools struggle to get integrated into the daily work if not perceived as directly necessary and clearly value-generating. This indicates that the challenge may not primarily lie in the availability of technological tools, but rather in transforming them into trusted and clearly value-creating integrated components in decision-making processes.

Furthermore, this defensive user-driven utilization can be argued to have implications for the future adoption of more advanced technologies, such as AI and CV. This is also something that became prominent during the AI discussions of the interviews, where the interviewees highlighted concerns regarding data handling and processing concerning confidentiality and sensitive project-specific data as major barriers to accelerating AI implementation and utilization in their daily work. If relatively simple and easily accessible tools, despite their heavy reliance on manual data collection, are not integrated into core workflows, it raises questions about the readiness of the industry to adapt more automated and data-driven approaches.

Overall, the findings emphasize that technological advancements alone are insufficient to drive change and to create value in construction project management. Instead, the value of visual site data depends on whether the technology is reliable, continuously updated, and embedded into everyday workflows. This shows the importance of user acceptance, perceived value, and organizational readiness to be able to utilize the full potential that technological developments enable. Thereby, the findings can be linked to the traditionally conservative nature of the construction industry. This, in turn, indicated that the challenge may not lie in the access to digital tools, but rather in transforming them into integral components of decision-making processes, which can be understood as a broader cultural and organizational challenge within the construction sector.

5.3 Risk analysis: safety, surveillance, and unintended consequences

Apart from the practical barriers discussed in the previous section, recording and using visual site data also introduces risks related to safety, surveillance, and responsibility. These risks are important to consider before such tools are further integrated into project management practices.

5.3.1 Reduced physical presence and unintended consequences

A potential risk that was raised during the workshop was that SiteWalk and similar visual documentation tools may reduce the perceived need for physical presence on the construction site. By providing project actors with the possibility to follow the project progress remotely, greater flexibility and easier access to site information are created. While this enables project manager practices to be streamlined, the workshop participants emphasized that physical presence remains essential, particularly from a safety perspective. A concern was raised that if remote control and digital visualization gradually start replacing regular site visits, there could be a risk that situational awareness and informal safety monitoring will be weakened.

This risk becomes particularly relevant because construction sites are dynamic and complex environments, involving dependencies between different actors and operations (Lafhej et al., 2024; Purushothaman et al., 2024). Previous research shows that safety performance during execution is affected by changing working conditions and workers' ability to identify and manage risks in daily operation (Smita & Bhole, 2016; Kinga Wasilkiewicz et al., 2024). Smita & Bhole (2016) argue that many construction accidents occur due to poor risk identification and unsafe working conditions. At the same time, Kinga Wasilkiewicz et al. (2024) emphasize that safety is closely integrated with daily project management and cannot be managed through technical systems alone. This highlights that the shared responsibility between white and blue-collar workers is essential for maintaining safe working conditions.

Physical presence on site also fulfills an important function from a behavioral and safety perspective. As one of the workshop participants claimed, the knowledge that site managers, site supervisors, or other officials are regularly moving around the workplace clearly contributes to blue-collar workers following safety procedures to a greater extent and avoiding unnecessary risks. This type of informal safety presence and social control is difficult to replace with remote control and digital visualization. Thus, the findings suggest that if the human presence on site decreases, there is a risk that the safety culture may be negatively affected over time.

From this perspective, visual access to the construction site is not the same as physical presence. While a 360°-image can show visual conditions at a specific occasion, it can not capture movement, interactions, work rhythms, or changes in the surrounding environment. Thereby, it is a risk that digital visualization creates a false sense of overview and control. This suggests that, although the technology could serve as a support for increased access to information, it should not replace the direct site observations and spontaneous interactions that are central for maintaining a healthy safety culture and situational understanding on the construction site.

5.3.2 Surveillance, trust, and worker integrity

Although the workshop discussions emphasized that physical presence and surveillance on site may contribute to a better safety culture and compliance with safety procedures, continuous digital documentation that is stored over time may not necessarily have the same positive effect. Another risk, therefore, concerns worker integrity and possibly the experience of surveillance. Continuous visual documentation can be introduced with the aim of improving documentation, coordination, and safety work. However, it can also be perceived as a tool for controlling individuals and work performance if its purpose is not clearly communicated.

This issue should therefore be seen not only as a technical problem but also as an organizational and cultural matter of trust. Previous research has highlighted that the implementation of DTs and AI-based systems within construction execution risk affects both organizational processes and relationships among project actors and stakeholders (Sacks et al., 2020; Laamanen et al., 2025). Sacks et al. (2020) emphasize that the concept of DTs in construction encompasses not only physical objects but also social systems involving people, organizational structures, and decision-making processes, as stated in the quote on page 13. The implementation of visual documentation tools may thus affect relationships among workers and positions, in addition to information flows. There may be a risk that acceptance and trust in the systems will decrease if workers begin to perceive the technology as a form of surveillance. This aligns with Laamanen et al. (2025), who emphasize that there is a need for further research into whether and how continuous AI-based observation negatively impacts motivation, autonomy, and organizational behaviors if the technology is perceived as controlling rather than supportive.

To address this risk, it is necessary to clearly state to all project stakeholders why the data is collected, who has access to the material, for how long the information will be stored, and how it is planned to be used and create value. This highlights the importance of transparency and clear governance of data. Anonymization and blurring of individuals are examples of important measures to protect privacy that Dalux SiteWalk takes, but are not necessarily sufficient in themselves, since the surrounding construction environment can reveal the identity of the blurred people. It will, therefore, be important with establishing clear routines for data handling in order for the technology to be perceived as a support tool rather than controlling. This also aligns with previous research that emphasizes that data quality, accountability, and human trust are key factors for implementing AI-integrated DTs (Omrany et al., 2023; Yang et al., 2024).

5.3.3 AI-related safety risks and false confidence

The results from the practical tests in Section 4.5, which used AI and 360°-images to identify safety hazards on construction sites, indicate multiple risks associated with AI-supported safety analysis. The results show that the AI model could identify some safety issues, but also demonstrated a tendency to over-identify and generate false assumptions before complex nouns was introduced. In the first round, 50% of the results were classified as overshot positives, meaning that the model identified the captured risk but also made at least one incorrect assumption or hallucination. Although over-identification is better than not identifying at all in terms of safety, it can be argued that it contributes to cognitive overload and reduced trust in the system. If users are exposed to these irrelevant and exaggerated warnings over and over again, there is a risk of so-called alarm fatigue, where warnings begin to be ignored or questioned (Woo & Bacon, 2020), potentially harming the safety aspect.

Meanwhile, 20% of the issues were missed completely. In safety-critical environments, like construction, missed risk identifications can have serious consequences, especially if users begin to rely too heavily on automated analysis. In addition, vision-based systems mainly analyze what is visually available, meaning that risks connected to working processes, methods, human behavior, or contextual factors may be overlooked.

However, after introducing complex nouns that were relevant to the gathered 360°-images from a construction site, the results became more in line with those from Yakupogullari et al. (2026). As the initial work had complex nouns that are relevant to their scenes as well, this indicates that information introduction regarding existing conditions on site is necessary to enable higher accuracy with AI systems.

AI-based systems are often seen as technically advanced and objective. However, this interpretation risks leading to the users perceiving the generated analyses as more reliable than they actually are. At the same time, previous research emphasizes that AI-integrated DT solutions are still highly dependent on data quality, contextual understanding, and human interpretation and judgment (Laamanen et al., 2025; Omrany et al., 2023; Yang et al., 2024), which has also been frequently emphasized across the interviews. This shows that human assessment and critical interpretation of AI outputs remain crucial. Consequently, this suggests that such tools should be understood as complements to existing practices rather than replacements for them.

5.4 The potential of AI-enhanced vision-based digital twins in construction project management

The results of this study indicate that the current use of visual site data could be compared with an early maturity level of vision-based DTs, corresponding to a maturity level between I and II in Table 2.1. In its current form, the visual site data primarily supports documentation, visualization, accessibility, and traceability. However, interpretation and extracting actual data from these images to be used for decision-making remain dependent on human assessment. This is in line with the literature concerning DTs, where more advanced DTs are described as systems that enable data exchange, analysis, and feedback between the physical and digital environment (Kritzinger et al., 2018; Sacks et al., 2020; Tao et al., 2019). Vision-based site documentation at its current state can therefore be understood as a start in a maturation process, where the digital representation is in place, but with automated analysis and predictive functions still being limited.

Given the results, AI is clearly a central mechanism for the future, in which visual site data can be developed towards higher DT maturity levels. While visual documentation makes site conditions available, AI and CV can potentially translate the gathered material into structured project information. The future value, thus, does not lie in collecting more 360°-images. More important is the ability to transform visual data into insights that can support project management and governance practices. This interpretation aligns with the literature regarding AI and DTs, where AI is described as a key enabler for automated analysis, prediction, and decision support (Kreuzer et al., 2024; Qi & Tao, 2018).

Furthermore, the results show several potential application areas for an AI-enhanced vision-based DT concept, including progress tracking, cost validation and control, schedule planning and follow-ups, quality assurance, logistics, safety support, and as-built documentation. In terms of progress and cost control, AI could contribute to more continuous validation of completed work, thereby reducing the reliance on manual estimates with uncertainties. This aligns with research on vision-based progress monitoring, where visual data and digital models are used to compare actual production with planned activities (Hsieh et al., 2026; Pal et al., 2023). Similarly, AI-supported analysis can potentially strengthen quality assurance and safety work by identifying visible deviations, risks, or incomplete work steps. This is also highlighted in the literature on DTs for quality and safety during the execution phase (Han et al., 2025; Reja et al., 2024; Yue et al., 2025).

Meanwhile, the results show that AI-enhanced visual site data is not yet mature enough to serve as an autonomous project management system. The data implementation is also affected by data restrictions, confidentiality, project-specific requirements, and the need for contextual interpretation. The practical AI analysis for identifying safety hazards reinforces this, as the results demonstrated that the AI-model both over-identified and missed risks both before and after refining the AI-prompt vocabulary. This shows that AI can contribute to increased safety awareness, but also that the results need human validation to avoid false assumptions or reduced trust. The literature on CV supports this interpretation, as automated image interpretation is dependent on contextual understanding and is influenced by the spatial relationships of the scene, the context of the object, and the complexity of the environment (Alamri & Pugeault, 2020; Koulalis et al., 2022; Zhou et al., 2025). This, once again, highlights that AI should be understood as a complement to human judgment, not a replacement for it.

This means that vision-based DTs in construction project management should not be seen as ready-made systems that create value directly when implemented. Instead, their value develops gradually, from visual documentation to more advanced analysis and decision support, as the technology is integrated into the project's workflow and decision-making processes. The development does not solely depend on improved image acquisition and more advanced AI-models, but also on how the visual data is integrated into the project's routines and workflow, linked to actual decision-making processes, and trusted by users. Compared to alternative intensive scanning-based methods, vision-based solutions can offer a practical path towards DT implementation during the execution phase, particularly when frequent updates and availability are more important than geometric precision (Koulalis et al., 2022; Shinde et al., 2023). Thus, it can be concluded that the maturity of vision-based DT solutions is both technical and organizational.

This highlights the potential strategic benefit of starting to implement lower maturity levels of vision-based DTs, even before more advanced AI and decision support functions are fully developed. Although current solutions primarily support documentation, visualization, and traceability, they can help organizations to develop their workflows, data routines, and user skills and familiarity required to later benefit from more advanced functions. Since DT maturity can be understood as a gradual evolution from representations toward analysis and decision support (Kritzinger et al., 2018; Tao et al., 2019), early use of simpler solutions can serve as a preparatory implementation phase. Lower maturity DTs thus become a way to adapt to an organization's way of working for future technological developments.

5.5 Proposed framework: From visual documentation to decision support

The results, based on the study's literature review, interviews, workshop, and practical testing, are condensed into a conceptual framework that illustrates the maturity level of vision-based DTs in the construction execution phase. The framework demonstrates the potential value that can be utilized at every maturity level, which increases progressively with each step, as shown in Figure 5.1.

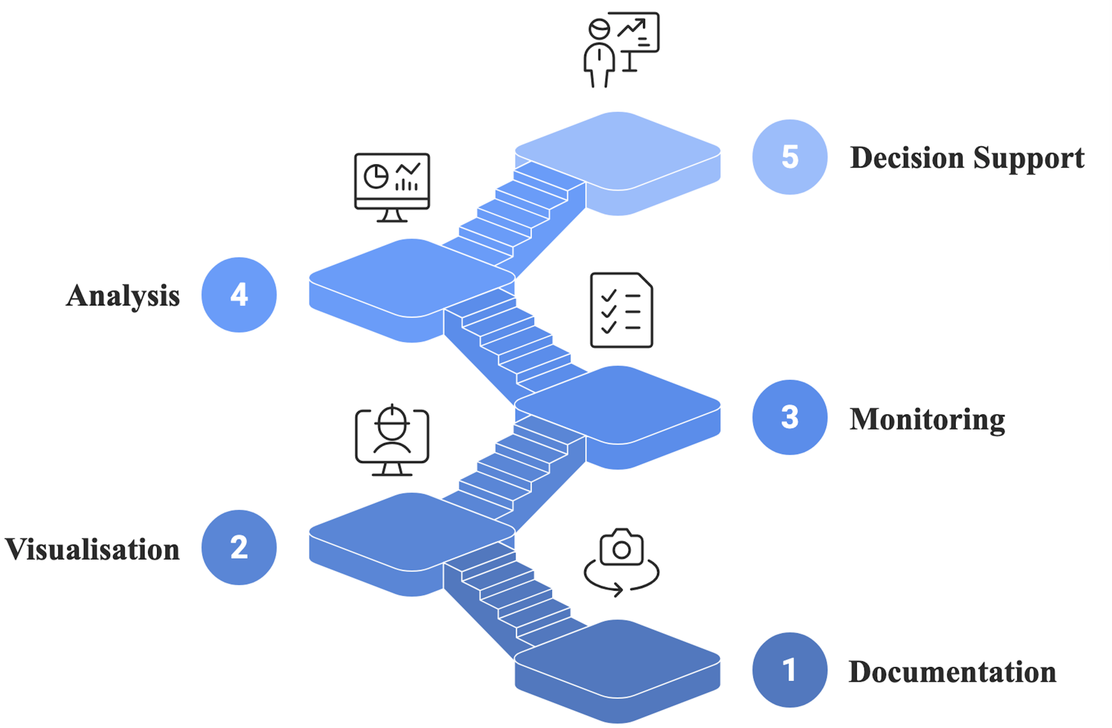

Figure 5.1: Illustration of the proposed digital twin maturity level framework.

The proposed framework lays its foundation on the idea that the implementation of vision-based DTs should not be seen as an all-or-nothing issue, where an organization either has the technology fully or lacks it completely. Instead, the study's results indicate that implementation can be done progressively through increased integration of visual documentation in BIM models, AI capabilities, and decision support processes. However, an important aspect to highlight is that the technology has not yet reached the level of development and practical establishment within project management in construction execution that is required to enable the higher levels of maturity. Thus, the framework should be considered as an illustration of current value creation and as an indicator of future potential.

Starting at the lower levels of maturity, the framework places its main focus on visualization, transparency, and documentation. At this level, the DT functions as a visual support tool through 360°-imagery linked to traditional drawings or BIM models. Already at this level, it can provide significant value through improved communication, remote inspections, progress monitoring, and increased situational awareness. The results show that these functions can contribute to reducing fragmented information flows and gaining access to reliable site information. Thereby, the lower maturity levels value creation is more connected to increased transparency and accessibility to project information rather than automation.

Furthermore, as the maturity level increases, the framework shifts towards semi-automated interpretation and analytical support. At this level, AI and CV are integrated into the workflow. Instead of generating a visual documentation of the site condition, the DT can support, for example, detecting deviations, progress monitoring, and identifying safety hazards through automatic or semi-automatic analysis of visual site data. The study's practical testing illustrated that AI-supported analysis can identify certain safety risks and interpret site conditions in 360°-images. However, this should not be understood as a fully reliable or mature process, but rather as an indication of potential. Notably, identifying safety hazards is just an example of how 360°-images combined with AI and CV can generate value. Another example could be material inventory and logistics on-site, which were identified as a desired potential in the interviews.

In the higher maturity levels, the framework develops toward more proactive and predictive support for project management. In theory, continuous data collection, AI-based interpretation, and BIM-integration could enable the DT to function as a dynamic decision support system instead of just a visualization platform. This maturity level, however, requires more advanced and reliable AI models, stronger system integration, and standardized workflows than what are typically available today. These higher levels of the framework should therefore be understood as a potential future-oriented development direction that requires significant improvements in maturity level regarding both technological developments and organizational willingness and preparedness.

An important contribution of the framework is therefore the relation between maturity level and value creation. Discussion about DTs in existing literature often suggests that a high level of technical maturity is required before clear benefits can be achieved. However, the results from this study show that this does not have to be the case, indicating that organizations and projects can generate practical value already in the early maturity stages. This becomes particularly important in the context of a construction project, where high implementation costs, organizational resistance, and fragmented workflows often limit the adoption of new technologies and working methods.

In addition to the importance of technological progression, the framework also shows that maturity development depends on changes in organizational and managerial structures. As emphasized by several interviewees, the main challenges may not be gathering visual data but rather integrating the technology into existing workflows and decision-making processes. This highlights the importance of building user acceptance, ensuring smooth process integration, and delivering clear practical benefits for the project organization, in addition to improved AI capabilities and technical infrastructure.

Lastly, the framework gives an idea of how vision-based DTs can support the broader transition from Construction 4.0 toward Construction 5.0. While low maturity levels mainly help in improving efficiency and information availability, higher maturity levels have the potential to support proactive safety management, human-centered decision making, and reduced cognitive workload for managerial roles. This suggests that the early implementation of vision-based DT concepts is motivated, not only by the value that can already be generated at lower levels, but also by the potential gain of preparing for future technological developments and new working methods. As the findings indicate, introducing new digital tools in a conservative industry requires user acceptance, significant organizational learning, and gradual integration in daily workflows, which is built stably over time. This suggests that construction organizations may benefit from starting to use these tools before more advanced AI-driven features are fully mature. With this approach, organizations can gradually build competence, establish clear routines, and standardize the use of visual site data in project management. This, in turn, can enable better utilization of the full potential of more automated and proactive DT systems in the future when the necessary technology is sufficiently developed and available.

6
Conclusion

This study aimed to answer the research question: *How can vision-based DT solutions evolve from passive documentation tools into decision-support systems to enable more proactive project management during the construction execution phase?* Based on the literature review, practical testing, interviews, workshop, and AI-based analysis of 360°-images, the study shows that vision-based DT solutions have the potential to evolve from mainly visual documentation tools to more integrated decision-support systems. To enable this, the tools both need to provide project teams with access to visual and up-to-date information about site conditions, but also, and more importantly, contribute to the interpretation, structuring, and use of this information in the project management decision-making processes.

A major finding with today's vision-based DT solutions is that they primarily create value through documentation and visualization, rather than a fully automated decision support system. The study's empirical reference point, Dalux SiteWalk, can support project teams by documenting site progress, comparing as-built conditions with as-designed BIM models, and enhancing communication between different stakeholders in projects. Thus, vision-based DTs can reduce fragmented information flows and improve situational awareness. This is also an important prerequisite to manage time, cost, quality, and safety in a dynamic construction environment.

However, the current impact vision-based DTs have on project management is primarily indirect. Vision-based DTs do not automatically improve time and cost management, or safety performance, merely on implementation. Instead, the contribution lies in better and more accessible information that can support earlier deviation detections, improved coordination, and more proactive follow-up. To develop into useful decision support systems, the solutions therefore need to be able to analyze visual site data to a greater extent, identify relevant deviations, and connect these to project management needs.

In terms of safety, the AI-based analysis of 360°-images demonstrated potential to identify certain risks on the construction site. However, the results also showed that such an analysis is still dependent on human validation and contextual understanding. AI is therefore suggested to be understood and used as a complement to professional judgment. This interpretation becomes central in the evolution from passive documentation to decision support. The technology not only needs to gather data, but also help to filter, interpret, and present relevant information in a way that supports human decision-making.

Furthermore, the results demonstrate that vision-based DTs are more suitable than LiDAR- or laser scanning approaches for supporting project management practices during the construction execution phase, as they offer a practical balance between update frequency, usability, and cost. In addition, vision-based solutions are less geometrically accurate, but perform better in dynamic environments. However, their reliability is affected by factors such as image quality, lighting conditions, camera placement, system compression, and the visibility of objects in the collected data.

Further on, the results also show that there are more than technical limitations to tackle, which are organizational and workflow-related barriers. SiteWalk was revealed to be used inconsistently and heavily depends on individual initiatives rather than being a standardized work approach. This limits the potential value creation of the tool, as vision-based DT solutions are required to be integrated within the daily project management practices to support decision-making. To avoid becoming just another documentation tool, it is essential to establish clear procedures regarding when data should be collected, who should use it, how it should be interpreted, and how identified deviations should be handled.

Lastly, the implementation of vision-based DTs should be comprehended as a gradual maturation journey. At the lower levels of maturity, value is produced through visual documentation, traceability, and enhanced communication. Further up in the staircase, as the maturity increases, AI and CV can enable semi-automated interpretation, detect deviations, identify safety hazards, and be more predictive in project management. However, to achieve these higher levels of maturity, organizational readiness, standardized workflows, user trust, and clear practical use are essential, apart from improved AI models and system integration.

Several conditions limit how the study's results should be interpreted. The empirical material is mainly based on Peab's organizational context, a limited number of interviews, a workshop, and practical testing of Dalux SiteWalk. The results should therefore not be seen as fully generalizable to all construction companies of various sizes, project types, or DT platforms. In addition, the AI-based safety analysis was exploratory and built on a limited number of 360°-images. These results should therefore be interpreted and seen as an indication for future potential AI-automated analysis. Together, these limitations highlight that the practical value of vision-based DT concepts depends on the project context, user adoption, workflow integration, and the maturity of supporting technologies.

To conclude, the study shows that vision-based DT solutions can evolve from passive documentation tools to decision support systems. However, this requires a combination of improved visual data collection, AI-driven analysis, clearer workflows, and a concrete plan for organizational integration. Its current practical value is primarily found in strengthening documentation, communication, transparency, and situational awareness. Meanwhile, its future potential lies in supporting earlier deviation identification, more systematic follow-up routines, and more proactive project management in general. Therefore, vision-based DTs should not be understood as a ready-made solution to the project management challenges of construction execution. Instead, it should be seen as an emerging support system whose value increases in line with technical, organizational, and user maturity.

6.1 Recommendations for future research

This study highlights several areas that could be further investigated in order to evaluate the potential value of vision-based DTs in construction, both in terms of broader implementation, value in various project types with various complexity levels, technological development, and human and organizational consequences.

Firstly, it is suggested that future research could further investigate how vision-based DT solutions can be integrated into daily project management routines and standardized workflows, with the aim of establishing a more concrete implementation plan. Since this study shows that organization integration is a central prerequisite for the value creation potential, future studies should investigate how roles, division of responsibilities, data collection routines, and decision-making processes need to be adapted for these tools to become a natural part of daily work.

Secondly, future research could evaluate vision-based DT solutions in a broader range of construction projects, companies, and contract types. This would make it possible to compare how the value of these tools varies depending on project size, complexity, organizational structure, and digital maturity. Comparative studies between different platforms, such as Dalux SiteWalk and more AI-driven systems, could potentially provide a clearer understanding of which features create the most value for project management and which are motivated to automate.

Thirdly, it is also recommended that future research investigate the total cost perspective of implementing vision-based DT solutions. This could include direct costs for licenses and necessary equipment, as well as indirect costs related to training, changed work routines, data collection, administration, and organizational implementation. At the same time, it would be beneficial to compare such costs with potential benefits, including reduced need for rework, fewer physical site visits, earlier deviation detection, improved progress follow-ups, and reduced risk for delays and cost overruns. Such an analysis could contribute to a clearer understanding of the actual practical business value and economic sustainability of the solutions.

Fourthly, future research could investigate more potential uses for AI-driven analysis of 360°-images. In addition to safety hazard identification, such applications could include, for example, production monitoring, deviation detection, material and logistics planning, quality control, and support for coordination between different actors, all of which were identified as desired areas of automated processes in the findings of this study. Furthermore, future studies could investigate how the reliability of AI-generated results is affected by varying site conditions, such as image quality, lightning conditions, object visibility, and workplace complexity.

Lastly, it is recommended that future research investigate the human and organizational implications of AI-enhanced DTs. This could include issues related to user trust, perceived surveillance, data integrity, and how professional judgment should interact with automated analysis. Understanding these aspects is crucial if vision-based DTs are to evolve from visual documentation tools to trusted and practical decision support systems in construction project management.

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A

Appendix 1

Table A.1: Summary and comparison of the two digital twin approaches.

Aspect	LiDAR- and laser-scanned digital twins	360-image and vision-based digital twins
Data & technical characteristics		
Primary data source	• LiDAR scanners, terrestrial or mobile laser scanners	• 360° cameras, fixed/mobile cameras, UAV imagery
Data type	• Dense 3D point clouds	• 2D images, 360° panoramas, video streams
Core principle	• Geometric reconstruction of the built environment	• Visual perception and appearance-based state recognition
Geometric accuracy	• Very high (millimetre–centimetre level)	• Lower, relative and appearance-based
Processing approach	• Point-cloud registration and geometric modelling	• Computer vision and machine-learning pipelines
Operational characteristics		
Update frequency	• Low to moderate (periodic scans)	• High (frequent or near real-time capture)
Data acquisition cost	• High (specialised equipment and expertise)	• Relatively low (commercial cameras and drones)
Scalability	• Limited by cost and logistics	• High across large and dynamic sites
Environmental sensitivity	• Robust to lighting; sensitive to occlusion and reflectivity	• Sensitive to lighting, camera placement, and occlusions
Functional focus		
Focus of representation	• Spatial geometry and as-built accuracy	• Site conditions, activities, and progress states
Role of BIM	• Geometric reference for verification	• Semantic and schedule reference for progress inference
Typical applications	• Dimensional checks, as-built documentation, quality control	• Progress monitoring, safety monitoring, remote inspections
Project management relevance		
Suitability for dynamic site monitoring	• Moderate	• High
Suitability for project management support	• Indirect (verification-oriented)	• Strong (continuous monitoring and decision-support)
Overall role in construction DTs	• Precision-oriented digital representation	• Management-oriented situational awareness tool

B
Appendix 2

Figure B.1: Correctly identified hazard = Positive AI-generated output.

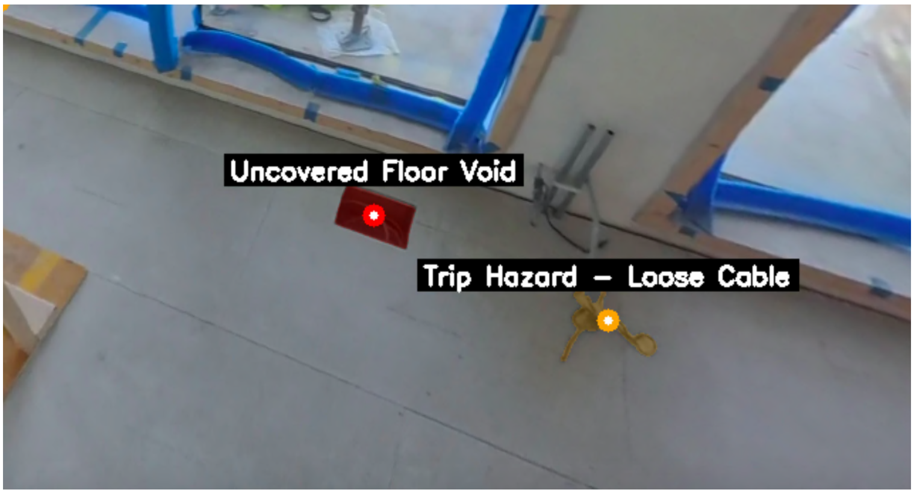

Figure B.2: Correctly identified hazard plus a false assumption = Overshot Positive AI-generated output.

Figure B.3: False identified hazard = Negative AI-generated output.

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