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Total BIM: Toward transforming construction

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Abstract

Building Information Modeling (BIM) was expected to rapidly transform the construction industry, but its uptake has been unexpectedly slow. Furthermore, even state-of-the-art BIM projects have been challenged by hardware and software issues, limiting BIM's implementation in the construction phase. This research explores an emerging approach to construction: Total BIM. Total BIM embraces BIM in its totality in that BIM is actively used in the construction phase by implementing model-based construction processes. It replaces 2D drawings as the legally binding source of information, enabling site workers to interact with modern cloud-based BIM software to create and extract necessary and relevant information.

Until recently, there has been a lack of real-world cases successfully implementing BIM as the single source of information for construction workers, which has hindered the possibility for researchers to explore the use of Total BIM in practice. However, this is beginning to change in Sweden and Norway, with the emergence of pioneering Total BIM projects. The purpose of this study has been to explore how Total BIM can be implemented as a single source of information across the design and construction phases of real-world projects. To achieve this, three in-depth case studies were conducted, collecting qualitative data from semi-structured interviews, observations, workshops, and more.

The findings, presented in four appended papers, demonstrate that implementing Total BIM in construction projects is possible and may even be preferred compared with traditional ways of working. Total BIM could serve as the missing link for advancing digitalization in the construction industry. Construction workers become an important part of structured data creation, through integrated processes such as requests for information (RFIs), controls, checklists and photos. This structured data enables new opportunities for informed, data-driven decision-making and site monitoring.

This research contributes rich empirical data from real-world case studies of Total BIM projects, illustrating how Total BIM overcomes limitations observed in previous state-of-the-art BIM projects. Additionally, it questions whether Total BIM could represent the digital disruption that the construction industry has been missing. For practitioners, this research provides real-world examples from Total BIM projects, demonstrating Total BIM implementation and highlighting key processes, while highlighting how Total BIM can create value.

Keywords: Building Information Modeling, BIM, Model-based construction, Drawingless, Data-driven construction, Total BIM.

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Appended papers

Paper I:

Embracing BIM in its totality: a Total BIM case study

Disney, O., Roupé, M., Johansson, M., & Domenico Leto, A. (2022). Embracing BIM in its totality: a Total BIM case study. *Smart and Sustainable Built Environment*.

Paper II:

Total BIM on the construction site: a dynamic single source of information

Disney, O., Roupé, M., Johansson, M., Ris, J., & Höglin, P. (2023). Total BIM on the construction site: A dynamic single source of information. *Journal of Information Technology in Construction (ITcon), 28(27), 519-538*.

Paper III:

Driving circularity with Total BIM: an integrated approach to data-driven design

Disney, O., Roupé, M., & Johansson, M. (2023, September). Driving circularity with Total BIM: an integrated approach to data-driven design. *In Proceedings of the 39th Annual Association of Researchers in Construction Management Conference (ARCOM), 2023, Leeds, United Kingdom*

Paper IV:

Digital disruption in the construction sector: going all-in with Total BIM

Duman, D.U., Disney, O., Roupé M., Johansson, M., & Claeson-Jonsson, C. Digital disruption in the construction sector: going all-in with Total BIM. *Work in progress paper.*

Additional publications

Total BIM project: The future of a digital construction process

Disney, O., Johansson, M., Leto, A. D., Roupé, M., Sundquist, V., & Gustafsson, M. (2021, December). Total BIM project: The future of a digital construction process. *In: Proceedings of the 21st International Conference on Construction Applications of Virtual Reality, 8-10 December 2021, 21-30.*

'Total BIM' as a Digital Disruption

Disney, O., Duman, D.U., Roupé M., Johansson, M., & Claeson-Jonsson, C. (2022, September). 'Total BIM' as a Digital Disruption. *In: Proceedings of the 38th Annual ARCOM Conference, 5-7 September 2022, Glasgow, UK, Association of Researchers in Construction Management, 32-41.*

Cost-Estimation in Construction: BIM versus 'Total BIM'

Påsse, D., Disney, O., Roupè, M., and Johansson, M. (2022, September). Cost-Estimation in Construction: BIM versus 'Total BIM'. *In: Proceedings of the 38th Annual ARCOM Conference, 5-7 September 2022, Glasgow, UK, Association of Researchers in Construction Management, 52-61.*

Total BIM in practice: a dynamic single source of information on the construction site

Disney, O., Roupé, M., Johansson, M., Ris, J., & Höglin, P. (2022, November). Total BIM in practice: A dynamic single source of information on the construction site. *In: Proceedings of the 22nd International Conference on Construction Applications of Virtual Reality, 16-18 November 2022, Seoul, South Korea, 874-885.*

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1 Introduction

Building Information Modeling (BIM) has long been hyped as having the potential to revolutionize the construction industry (Azhar, 2011; Sacks et al., 2018). Adopting BIM leads to many benefits, including reducing the industry's fragmentation (Eadie et al., 2013; Fadeyi, 2017), improving productivity (Zhang et al., 2017), and generating cost savings (Chahrour et al., 2021). However, despite these claims, the adoption of BIM in the construction industry remains slower than anticipated (Azhar, 2011; Ghaffarianhoseini et al., 2017; Sacks et al., 2018; Samuelson and Stehn, 2023; Walasek and Barszcz, 2017).

Traditionally, BIM is implemented in the design phase for coordination and clash detection (Davies and Harty, 2013; Eadie et al., 2013). During this phase, parallel to BIM development, 2D drawings are created as the primary information source for construction workers due to being well tested and trusted in practice. However, the production of these 2D drawings limits the resources available for further BIM development, resulting in infrequent updates to BIM, and rendering it an unreliable source of information for construction workers. Consequently, few real-world building projects have implemented model-based construction processes (Brooks et al., 2023) due to the absence of reliable BIM data. Furthermore, projects that attempted to implement model-based processes have encountered limitations stemming from hardware and software issues (Aune, 2018; Bråthen and Moum, 2016; Budarina, 2017; Cousins, 2017; Davies and Harty, 2013; Mershbock and Nordahl-Rolfsen, 2016; Rybus, 2022; Trafikverket, 2013; Ulvestad and Vieira, 2021).

A new model-based approach to construction is emerging in Sweden and Norway, known as Total BIM (Cousins, 2017). Total BIM is an approach where BIM is "embraced in its totality" (Cousins, 2017), serving as the single source of information throughout all project phases. It replaces traditional 2D paper drawings with BIM and model-based construction processes are implemented. To achieve this, BIM is enforced as the legally binding source of information for both designers and construction workers, and site workers interact with the cloud-based BIM on mobile devices to create and extract construction information.

The parallel production of 2D drawings alongside BIM, coupled with hardware and software issues, has complicated the implementation of Total BIM. This has led to a lack of successful real-world cases of Total BIM processes being effectively implemented in the building sector. Consequently, researchers have thus far been unable to study the implementation of Total BIM building projects in real-world scenarios (Brooks et al., 2023; Tu et al., 2023).

This thesis aims to address this research gap and contribute to the body of knowledge for both practitioners and researchers by examining empirical findings from real-world pioneering Total BIM projects. In doing so, it seeks to address the barriers to BIM implementation in traditional projects and nudge the construction industry toward the anticipated transformative change that BIM was initially expected to bring about. The empirical data are based on findings from observations conducted during three in-depth case studies of Total BIM projects - one completed and two ongoing projects. These findings are further supported by qualitative data collected through interviews, workshops, site visits, and additional sources such as company presentations, documentation and on-site BIM platform access. The rich empirical data in this study are analyzed to further the understanding of what a Total BIM project entails, the implementation of Total BIM on construction sites, the potential for using data-driven approaches to improve sustainability, and whether Total BIM can achieve the digital disruption that has so far not been achieved in traditional BIM projects.

1.1 Purpose and research questions

The purpose of this thesis was to explore the emerging approach, Total BIM, and contribute to its development in both research and practice. To achieve this, rich empirical data were collected from three in-depth Total BIM case studies, using a combination of qualitative research methods, such as interviews, observations and workshops. While interviews formed the backbone of the empirical findings, they were complemented and informed by data collected during site visits and workshops involving a large reference group of leading construction digitalization experts. Three primary research questions were identified and considered:

> *RQ 1: What is Total BIM?*

Previous studies have highlighted that BIM has not transformed the industry as expected. One reason for this has been the continued reliance on 2D drawings at construction sites, which limits the resources available for BIM development. While some projects have attempted to adopt model-based processes, they have encountered significant challenges. This first research question aims to distinguish what differentiates a Total BIM project from traditional projects, as well as to identify the important requirements of Total BIM projects. This first question leads to the following research questions.

> *RQ 2: How can Total BIM be effectively implemented on the construction site?*

In traditional construction projects, site workers rely on 2D drawings as their primary information source, but this information is static and frequently leads to mistakes. Building on findings from the first research question, this question revolves around exploring how to implement Total BIM on construction sites. Site workers in Total BIM projects create and extract construction information using cloud-based BIM on mobile devices, which involves very different processes to reading 2D drawings. Hence, it is necessary to understand what processes and features are necessary for site workers to realize Total BIM construction and how these can be implemented in practice.

> *RQ 3: Why should we implement Total BIM: what are the outcomes of implementing Total BIM?*

This question considers whether Total BIM is the digital disruption that the construction industry has thus far been lacking. If it indeed is, several barriers to implementation may be overcome, such as replacing drawings with BIM as the legally binding source of information for both designers and construction workers. Therefore, it is important to evaluate the outcomes of Total BIM implementation, in terms of both the perceived benefits and the challenges, as well as what needs to be further improved. By fulfilling this research question, we can gain an understanding of the value created by Total BIM.

1.2 Structure of thesis

This thesis is structured in six chapters. Following the introduction, a review of previous research is conducted, which includes 2D drawings as an information source, BIM, model-based construction and Total BIM, providing a frame of reference. Chapter 3 provides an overview of the cases studied in this research and describes how the empirical data was collected and analyzed. Following this, a summary of the papers is provided, focusing on the findings and contributions. Chapter 5 offers a general discussion of the findings and contributions of this thesis. Finally, conclusions regarding implications for practitioners and researchers are presented, along with suggestions for future research.

2 Related studies and problem description

This chapter addresses the limitations of traditional information sources in construction projects and the current common uses of BIM. Additionally, it describes how model-based construction can extend the active use of BIM into the construction phase, despite multifaced challenges. The chapter ends with a description of Total BIM, which is a new model-based approach where BIM is actively used as the single source of information throughout all project phases.

2.1 Drawings in construction

Traditionally, drawings have been, and still remain, the primary medium for communicating the information needed for the construction of a building (Brooks et al., 2023; Eastman et al., 1974). Yet, drawings have long been criticized for inaccuracies and errors resulting in frustration, unanticipated costs, delays and lawsuits (Brooks et al., 2023; Davies and Harty, 2013; Eastman et al., 1974; Sacks et al., 2018).

Criticisms of drawings include:

- 3D information is conveyed in a 2D format; therefore, information must be duplicated (Eastman et al., 1974).
- Design changes mean that new drawings need to be produced, printed and delivered (Eastman et al., 1974), and changes are not always communicated appropriately (Aibinu and Venkatesh, 2014).
- Drawings contain static information created at a set point in time (Van Berlo and Natrop, 2015), which quickly become superseded (Gaunt, 2017).
- Drawings take a large amount of effort to produce, update and maintain (Aibinu and Papadonikolaki, 2020; Eastman et al., 1974), all of which are costly activities (Davies and Harty, 2013).
- Finding information from drawings for construction activities accounts for a large proportion of an assembly task's time (Brooks et al., 2023).
- Due to their physical format, drawings contain limited information that may not be the most suitable for construction workers (Van Berlo and Natrop, 2015).
- Drawings can be difficult to interpret, which leads to errors and time wasted on the construction site (Brooks et al., 2023).

Whilst drawings have long been unsatisfactory, they continue to be the default representation whether in digital or paper-based format (Davies and Harty, 2013), primarily due to being well tested in law and practice (Brooks et al., 2023). Whilst 2D drawings can be annotated, they are "dead" documents that are created at a static point in time (Van Berlo and Natrop, 2015). In contrast BIM is not merely a replacement for 2D drawings, it can potentially be a "live" dynamic source of information and transformation (Lu et al., 2018).

2.2 Building Information Modeling (BIM)

Azhar (2011) suggests that Building Information Modeling (BIM) is "one of the most promising recent developments in the architecture, engineering, and construction (AEC) industry," and adds that it allows stakeholders "to collaborate more accurately and efficiently than using traditional processes." However, despite the widespread acknowledgement of these benefits and the availability of BIM, it was found that BIM's rate of adoption was much slower than anticipated (Azhar, 2011; Ghaffarianhoseini et al., 2017; Sacks et al., 2018; Samuelson and Stehn, 2023; Walasek and Barszcz, 2017).

In recent years, the implementation of BIM has significantly increased, as reported by the National Building Specification (NBS) (NBS, 2023). According to their study of predominantly UK companies, BIM adoption has risen from 13 percent in 2011, to 70 percent in 2023 (NBS, 2023). Additionally, a study conducted in 2017 on medium-sized Swedish contractor firms showed that 58 percent used BIM (Bosch-Sijtsema et al., 2017). However, as noted by the NBS (2023), it is important to try to understand what it actually means to adopt BIM, as it can vary among different individuals and organizations. For some of the NBS's survey respondents, BIM was simply about working with 3D models, while for others it was about information management, and yet for others it involved following processes described in standards. In the study by Bosch-Sijtsema et al. (2017), BIM use was mainly limited to visualization purposes, to support communication and coordination. In Sweden, industry and academia collaborated to create a framework aimed at guiding research efforts in the holistic assessment of BIM (see Fig. 1) (Bosch et al., 2016; Sundquist et al., 2020). Analyzing BIM implementation according to this framework could support efforts to establish a common understanding of what BIM implementation entails and avoid some of the confusion that currently exists.

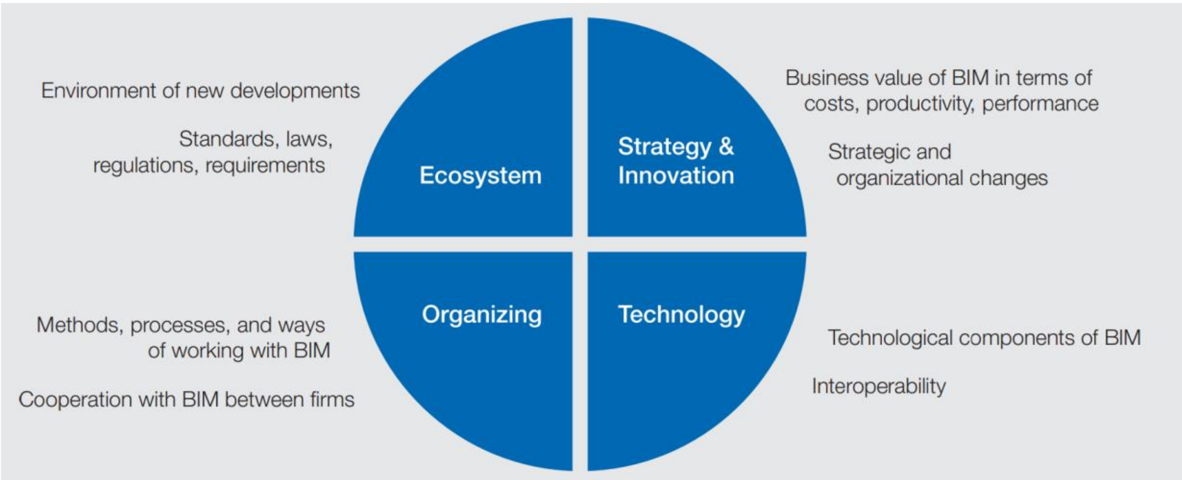

Figure 1. Holistic research framework to BIM implementation. (Bosch et al., 2016).

In part, the differences in understanding what BIM is arise from the existence of multiple definitions developed by researchers, industry bodies and software developers (Succar, 2009). Sacks et al. (2018, p. 14) defined BIM in the BIM handbook as "a modeling technology and associated set of processes to produce, communication, and analyze building models." It should therefore be understood as more than just a piece of software, or more than just a 3D model. Understanding what BIM is becomes more complicated in the context of the levels of implementation within a project.

"BIM Levels" have become widely used to describe the four levels (Level 0 to Level 3) of BIM compliance in a project (Sacks et al., 2018). These levels were depicted by Bew and

Richards (2008) in their BIM Maturity Model, which was later included in the UK PAS 1192-2:2013 BIM standard and described by Sacks et al. (2018) as:

- Level 0 BIM is unmanaged Computer Aided Design (CAD), and information exchange is likely to be based on paper drawings or digital PDFs.
- Level 1 BIM is a mixture of CAD and 2D, where data are shared in a common data environment (CDE), but models are not shared.
- Level 2 BIM is a collaborative way of working where designers use their own distinct models, but they do not work on a shared model. The models are shared using a common file format, which is then used to create a federated model.
- Level 3 BIM is not clearly defined, but has been referred to as Open BIM, where all the designers work in a shared model.

The current ISO 19650 standards reflect Level 2 BIM, which is founded on the preceding standards BS 1192:2015 and PAS 1192-2:2013 from the UK. Based on these standards the UK government mandated BIM for all centrally procured construction projects since 2016 (BIS, 2013). Government and private sector initiatives following these standards were expected to sharply increase BIM implementation, and those that did not embrace BIM would be left behind (Smith, 2014). However, as noted above, the adoption rate of BIM remains slower than expected (Azhar, 2011; Sacks et al., 2018; Samuelson and Stehn, 2023; Walasek and Barszcz, 2017) due to numerous barriers, such as high cost of implementation, lack of skills, organizational and legal issues (Eadie et al., 2013; Liu et al., 2015).

The title of ISO 19650 refers to “information management using building information modelling.” In this context, it outlines an information management process for projects and provides a generic framework for organizing project work using BIM. However, current standards lack the necessary technical details regarding BIM implementation (Lu et al., 2020). These omissions may prompt organizations to interpret the standards according to their own perspectives, potentially impeding progress toward Level 3 BIM. Given that Level 3 BIM involves increased collaboration within a shared model environment, adhering to common standards is essential.

Level 2 BIM has been widely used in the design stage to support coordination, automatic clash-detection, and collaboration (Davies and Harty, 2013; Eadie et al., 2013). However, in many such BIM projects, design activities still involve 2D drawings as they remain the primary legally binding construction documents and trusted communication medium for construction sites (Aibinu and Papadonikolaki, 2020). This means that even in projects using BIM, most are still using 2D drawings, resulting in two parallel processes that require increased time, cost and effort. Aibinu and Papadonikolaki (2020) found that drawing activities accounted for 41 percent of the total effort in the BIM process, partly because clients require them, and it takes a lot of effort to ensure that drawings are well presented. Until construction processes change, and model-based construction becomes more common, 2D drawing production will continue to detract from the resources to develop information rich BIM (Aibinu and Papadonikolaki, 2020). Therefore, even though BIM may currently exist on construction sites for coordination and visualization purposes (Bosch-Sijtsema et al., 2017; Sacks et al., 2018; Tu et al., 2023), it is rarely used for construction activities (Brooks et al., 2023).

2.2.1 Integrated Project Delivery (IPD) and Virtual Design and Construction (VDC)

As buildings become increasingly technically complex, project teams have become more specialized, leading to a fragmented approach to project delivery and information exchange (Fisher et al., 2017; Nepal and Staub-French, 2016 ; Samuelson and Stehn, 2023). Furthermore, the introduction of new technologies in the industry has been fragmented (Sacks et al., 2018). Given these challenges, it is necessary to adopt a strategy to integrate project teams and technology (Fisher et al., 2017). According to Fisher et al. (2017), Integrated Project Delivery (IPD) is an approach that aims to share risks and rewards for greater performance by creating a collaborative project organization. Furthermore, trust has been identified as a major barrier to increased digitalization in construction (Jaskula et al., 2024; Perera et al., 2023). IPD promotes information sharing, collaboration, and innovation among organizations and individuals, with the aim of fostering trust for improved collaboration (Fisher et al., 2017). In this context, BIM provides a platform for integrating information, while IPD facilitates the integration of teams.

Virtual Design and Construction (VDC) combines BIM and project management principles to optimize not only the design of a building but also the processes involved in its creation (Fisher et al., 2017). This approach enables stakeholders to collaborate simultaneously within a single repository to test solutions in a virtual environment (Lu et al., 2018). By combining IPD and VDC, teams can collaboratively explore solutions and strive to deliver optimized BIM solutions. One practical example of this approach might be through early contractor involvement to optimize design decisions, with all stakeholders working to maximize project value (Lu et al., 2018). However, despite early contractor involvement and efforts to optimize BIM development, the legally binding source of information at the construction site typically remains 2D drawings derived from BIM. If contractors possess sufficient expertise to participate during the design of BIM, why is BIM not actively used in the construction phase as a richer, dynamic source of information than what is contained in traditional drawings?

2.3 Model-based construction: affordances and current constraints

Although BIM is widely used during the design phase, its active use during the construction phase is notably less (Tu et al., 2023). However, studies have demonstrated the benefits of extending the use of BIM in the construction phase, making it crucial for realizing the value of BIM (Tu et al., 2023). As a replacement to traditional technical drawings, model-based approaches have driven advancements in the manufacturing, automotive and aerospace industries (Brooks et al., 2023; Quintana et al., 2010). Hedberg et al. (2016) studied manufacturing companies and found that the difference in design time for drawing-based and model-based approaches was negligible. Furthermore, they found that model-based approaches may save time, improve quality and reduce errors. Construction projects adopting a model-based approach may also reap these benefits (Gaunt, 2017), and eliminate some of the problems associated with 2D drawings and a limited approach to BIM.

When discussing model-based construction, it is important to understand what it implies. According to Gaunt (2017), model-based design delivery involves a “drawingless” design delivery process, and instead delivers a model to the client. Gaunt (2017) states that the model is the "single source of design truth," a notion mirrored by EFCA (2019), which claim that BIM "acts as a single source of truth for all information derived from it."

In this thesis, model-based construction refers to the use of BIM for construction activities, as opposed to traditional drawing-based approaches. This entails extracting information directly from BIM on construction sites, where BIM is the "single source of information" for the construction phase (Brooks et al., 2023). Consequently, the active use of BIM extends beyond the design phase. It is noteworthy that the concept of a "single source of truth" (EFCA 2019; Gaunt, 2017) is not used in this thesis because of the subjectivity inherent in truth. Furthermore, the terms "Site BIM" (Davies and Harty, 2013) and "Field BIM" (Sacks et al., 2018) are not used, as they do not necessarily imply model-based construction processes, but rather refer to various applications of BIM on construction sites using mobile computing devices.

Model-based construction projects are not common in the construction industry and few industry professionals can provide a clear explanation of model-based processes (Brooks et al., 2023). In the rare cases that projects have attempted model-based construction, implementation has often been limited. An early attempt at model-based construction occurred in the Swedish Röfors bridge project in 2013. However, at this time hardware and software did not function effectively enough for use on the construction site (Trafikverket, 2013). In more recent projects, it was found that since model-based processes are still novel, there are challenges with standard contracts, and stakeholders have limited digitalization capabilities (Budarina, 2017; Mershbock and Nordahl-Rolfsen, 2016; Rybus, 2022). The software used in model-based projects is often insufficiently developed for use on construction sites, lacking features for filtering and extracting measurements, and is aimed towards skilled designers rather than construction workers (Aune, 2018; Budarina, 2017; Rybus, 2022; Trafikverket, 2013; Ulvestad and Vieira, 2021). Furthermore, model-based construction projects have mainly been limited to the infrastructure sector or structural work, and few building projects have adopted the approach (Brooks et al., 2023).

When software and hardware do not function effectively for their intended purpose, they limit the extent to which model-based construction processes can be implemented. If they do not function effectively on construction sites, necessitating 2D drawings or Production-Oriented Views (POVs) to be generated from the model and printed on paper (Abu-Hawesh et al., 2020; Trafikverket, 2013; Ulvestad and Vieira, 2021), then many of the benefits of working with a single source of dynamic information are lost. Similarly, if drawings are produced in parallel to BIM, consuming resources in the process, workers will no doubt be tempted to fall back on traditional ways of working. Therefore, overcoming software and hardware issues is crucial for implementing model-based construction processes and a single source of information.

Mobile computing, a key requirement of the model-based approach, is becoming cheaper and more widespread due to advancements in device power, battery life and wireless connectivity (Brooks et al., 2023). With mobile computing becoming more widespread and the continual development of software for construction site applications, the increased digitalization enables access to large amounts of data that have previously only been available to designers. Providing this data in a structured and logical format, may facilitate improvements on construction sites, such as increased productivity, better communication, a greater level of accuracy and trustworthiness, reduced accidents and waste, higher quality, and a better understanding of complex geometry (Brooks et al., 2023; Perera et al., 2023). Despite concerns about the costs of implementing these tools and processes (Liu et al., 2015; Perera et al., 2023), studies have shown that implementing BIM can yield a positive return on investment (Eadie et al., 2013; Sompolgrunk et al., 2023), and that initial investment costs are affordable even for smaller companies (Eadie et al., 2013).

By prioritizing the development of BIM to ensure it accurately represents the intended construction, data can be exported directly for use in other applications such as Augmented Reality (AR) and Virtual Reality (VR), to improve planning, design reviews and informed decision-making (Johannson and Roupé, 2019; Johannson and Roupé, 2024). Moreover, in model-based construction projects, creating a digital twin for facility management purposes may be more straightforward compared to traditional projects, as an accurate BIM already exists for construction activities (Brooks et al., 2023).

2.3.1 Total BIM

Cousins (2017) initially introduced the concept of "Total BIM," to mean a project that is 100 percent digital, i.e., BIM is embraced in its totality. According to Cousins (2017), going 100 percent digital involves completely eliminating paper drawings, which can improve design coordination, efficiency and reduce costs. Consequently, it also eliminates the parallel processes of producing and maintaining 2D paper drawings and BIM.

In this thesis, my use of the phrase "Total BIM" develops the initial concept outlined by Cousins (2017), and aids in distinguishing between partial model-based projects and fully integrated model-based projects - a distinction that previous research has failed to clarify. Consequently, there has been a lack of clarity regarding what a Total BIM projects entails, what processes are necessary to achieve Total BIM, and the resultant outcomes of its implementation.

3 Research design and methods

The initial focus of this research was to understand what a Total BIM project entails, and the outcomes of its implementation. Accomplishing this required the exploration of how Total BIM differs from traditional construction and even model-based projects. This exploration process led me to conduct workshops and site visits with a reference group of industry digitalization experts. The interactions during these workshops and site visits, coupled with an extensive review of existing literature, provided me with background data for this research. This background data served to contextualize the research findings regarding Total BIM, facilitating the identification of important Total BIM themes and processes. While much of this background data is not directly presented, the insights gained from the data collection process significantly contributed to this research. Additionally, these insights helped in refining interview questions, which formed the primary data collected in this study. Moreover, discussions held during site visits and workshops were used to validate research findings.

The following chapter provides a description of the approach and methods used in this research. The chapter begins with a description of the cases. This is followed by the data collection methods used and concludes with a description of how the data were analyzed.

3.1 Description of the cases

This thesis draws on qualitative data collected from case studies of Total BIM used in building projects. Among these cases, three particularly stood out as significant to the findings, demonstrating new applications of Total BIM. Case study research is suitable when exploring new topic areas and for exploring complex phenomena within their real-world contexts (Yin, 2009). Moreover, case study research benefits from multiple data collection techniques, offering the opportunity to highlight significant empirical findings (Yin, 2009). The case projects in this research presented a unique opportunity to study the implementation of Total BIM.

3.1.1 Reference projects

In addition to the three main case studies, I collected background data from two additional projects. The first of these, Glasblokkene Trinn 2, completed in 2023, involved the construction of a new hospital wing in Norway using Total BIM. A site visit to the project was conducted in June 2022, and was followed by a workshop with the reference group. The project managers of Glasblokkene Trinn 2 demonstrated how they integrated construction worker expertise into the BIM design development process. Additionally, the project highlighted how digital tools can be used to support the implementation of Total BIM, the benefits of creating production-oriented BIM and showed how Total BIM was used on the construction site.

The second project contributing to background data collection was Nattugglan, which involved the construction of a new office building and was completed in 2022. The Swedish projects in this study were all managed by a small construction management (CM) company. The implementation of Total BIM in Nattugglan was similar to one of the company’s previous projects, Celsius. Therefore, while the project contributed to the interviewees’ experience and demonstrated the feasibility of Total BIM, it was not studied to the same extent as the project Celsius.

3.1.2 Primary case studies

Sweden has been recognized as a world leader for the level of BIM implementation in projects (Nemetschek, 2023). The three main cases studied in this research were identified by both the researchers and industry reference group as leading Total BIM projects.

The Celsius project was the initial focus of this research. Commencing in 2018, and completed in late 2020, Celsius, was the new construction of an office and laboratory building in Uppsala, Sweden. Motivated by mistakes encountered when working with traditional drawings in a prior project, the CM company decided to undergo a digital transformation and implement Total BIM. Celsius was the CM company's first attempt at implementing Total BIM, necessitating the development and refinement of numerous design and construction processes throughout the project. One example of this included resolving issues with hardware and software that had previously hindered BIM implementation in the construction phase. Thus, studying the Celsius case presented a unique opportunity to identify the differences between traditional BIM and Total BIM in projects.

After completing the Celsius project, the CM company further developed on their initial implementation of Total BIM in two ongoing projects: Lumi and SB47. SB47 is an office renovation project and has been chosen as a case study as it provided insights into how to implement Total BIM in renovation projects, where some existing structures had to be preserved, some demolished and others newly built. This presented challenges to the CM company in terms of how information should be displayed in BIM for construction workers.

The Lumi project is an ongoing mixed-use renovation project, involving the conversion of offices and laboratories to new offices, a hotel and housing. In this project, the CM company aimed to maximize the reuse of existing materials. This required the development of new Total BIM processes to integrate data between a material database, BIM during the design process and BIM on the construction site. Throughout the design process, sustainability data was used for informed, data-driven decision-making with the client and tenants, aiming to reduce the overall carbon footprint of the project.

These two ongoing projects demonstrated novel applications of Total BIM that contributed new empirical data that was not present in the Celsius case. Furthermore, since they were ongoing during the study period, they provided an opportunity to monitor progress and communication throughout the project, facilitated by access to the on-site BIM platform.

3.2 Data collection

This section provides a description and justification of the diverse qualitative data collection methods used, which includes interviews, workshops, observations from site visits, and complementary data such as seminars, and access to the on-site BIM platform. An overview of the data collection is provided in Table 1 below.

Table 1. Overview of the data collection

<table>
<tr><th></th><th>Paper I</th><th>Paper II</th><th>Paper III</th><th>Paper IV</th></tr>
<tr><td>Case projects</td><td>Celsius, Uppsala, Sweden</td><td>Paper II extends on Paper I by including data from 3 additional case studies

Celsius and Lumi, Uppsala, Sweden

SB47, Stockholm, Sweden

Glasblokkene Trinn 2, Bergen, Norway</td><td>Paper III extends on data from Papers I and II

Lumi, Uppsala, Sweden</td><td>Paper IV extends on data collected from Papers I, II and III

Celsius, Nattugglan, Lumi, and SB47, Sweden</td></tr>
<tr><td rowspan="3">* Interviews</td><td colspan="2">9 semi-structured interviews

2 project managers (VDC on-site engineer / strategist)

1 design and project manager

1 site manager</td><td></td><td></td></tr>
<tr><td></td><td>2 semi-structured interviews

2 project managers (VDC on-site engineer / strategist)

1 design and project manager</td><td></td><td></td></tr>
<tr><td></td><td></td><td>2 semi-structured interviews

1 project manager (VDC on-site engineer)</td><td>6 semi-structured interviews

2 project managers (VDC on-site engineer / strategist)

1 design and project manager

2 site managers

1 software developer</td></tr>
<tr><td rowspan="2">Workshops</td><td></td><td colspan="3">5 workshops with industry experts about the vision and implementation of Total BIM</td></tr>
<tr><td></td><td></td><td>1 workshop with the case company and a large contractor</td><td></td></tr>
</table>

Site visits		3 full day filmed site visits to three of the projects with the reference group *(Glasblokkene Trinn 2, Lumi and SB47)*	*Site visit to project Lumi in Paper II supported the data collection*	*Site visits from paper II supported the empirical data collection*
Miscellaneous	Internal documentation, company presentations, informal discussions			
		Observations from on-site BIM platform access *(Lumi and SB47)*		
		2 seminars with project managers		
Notes	* All interviews were between 1 to 2 hours in duration			

3.2.1 Interviews

The primary data collection method has been semi-structured interviews. Semi-structured interviews were deemed suitable for this research as they allowed for a focused exploration of key issues related to the topic of interest, as well as the opportunity to probe interesting accounts further in follow-up questions (Brinkmann, 2014). Collecting the primary data through interviews enabled me to gather detailed accounts of Total BIM implementation in the particular contexts of each case.

The interview data were collected through 19 semi-structured interviews, primarily including representatives from the case studies in Sweden, conducted between 2021 and 2023. Three interviewees were prominently featured in this research, all of whom were from the CM company. These interviewees were selected because they had been identified as key individuals within the company responsible for implementing Total BIM, and at the time of this research there were few individuals with expert knowledge in implementing Total BIM (Brooks et al., 2023). Two were project managers that were experts in digitalization and VDC. The third interviewee was a founding partner of the company, who had limited digitalization skills but had been instrumental in driving Total BIM within the organization.

Given that most of the interviewees worked at a single company, there is the potential for biases in the data. However, I aimed to mitigate these biases by referencing the interview findings with observations from study visits. Furthermore, the findings were discussed and validated during the workshops with the reference group who were at various stages of Total BIM implementation themselves.

All interviews were conducted online and lasted between 1 to 2 hours. With the permission of the interviewees, they were all recorded, and most were subsequently transcribed. For those that were not transcribed, detailed summaries were made. In addition to recording, the interviewers made notes during the interviews to capture key points or to serve as support for follow-up questions. Each new interviewee was asked to provide a brief description of their background and career trajectory to date. Following this, semi-structured questions were asked, allowing for further exploration of interesting points or clarification of any remaining points that were unclear to the interviewees. During some of the interviews, the interviewees opted to screen share to provide a visual demonstration of how they interacted with the software on construction sites. I conducted the interviews with the support of three other researchers involved in this study. Although I was not present during two of the interviews, I thoroughly analyzed the video recordings.

At the beginning of the research project, an explorative preliminary interview was conducted with one of the CM company's two digitalization leaders. The interviewee had overseen the implementation of Total BIM on the Celsius construction site. This preliminary interview helped me form an initial understanding of what a Total BIM project entailed, particularly since it was a novel approach.

Following this exploratory interview, eight interviews were conducted, with a specific focus on the Celsius case. The semi-structed questions asked during these interviews were guided by an existing BIM framework in the literature (Bosch et al., 2016) (see Fig. 1). This framework served as a starting point through which to structure interview questions into the four main themes, and eight sub-themes outlined within it. By following this structure, the aim was to identify the processes and outcomes of the CM company's implementation of Total BIM in the Celsius project and begin to create a shared understanding of what a Total BIM project entails.

The findings in Paper I, together with workshop discussions and site visits, highlighted the importance of how Total BIM was implemented and used on construction sites. Therefore, two further interviews were conducted for Paper II, aiming to specifically gather data on themes relating to how Total BIM processes had been implemented on construction sites. Paper III and IV expanded upon the existing findings by conducting new interviews and incorporating specific questions aimed at understanding how Total BIM could facilitate the increased reuse of materials in renovation projects, as well as exploring whether Total BIM creates a digital disruption. While the interviews primarily focused on projects undertaken by the Swedish CM company, the interview questions were informed from a more in-depth understanding of Total BIM from the workshops and site visits. Additionally, one interview was conducted with a software developer to understand how the on-site BIM platform had been developed to support Total BIM on the construction site.

3.2.2 Workshops

Throughout this research, a total of six workshops were conducted, which helped generate new insights into the research phenomenon, where the significance of insights was discussed and negotiated (Ørngreen and Levinsen, 2017). The aim of the workshops was twofold. Firstly, they aimed to gather insights for this research from a reference group of industry digitalization experts. Secondly, they sought to create a platform for knowledge sharing, enabling the reference group to benefit from insights into various applications of Total BIM, while also supporting the validation process of the research findings.

Five of the workshops were organized by the researchers in this study. These workshops began with 19 industry experts in digitalization, but this number grew to 35 over the course of the research project. The reference group participants had extensive industry experience ranging from 12 to 40 years and were based in Sweden and Norway. These workshops comprised of participants from two universities and sixteen companies, including four construction companies, nine design engineering companies, one real estate company, one government agency, and one software development company. The workshops were conducted and filmed with participants’ permission throughout 2022 and 2023.

The first of these workshops, lasting two hours, was conducted online at the beginning of this research project in January 2022. Although many in the reference group were aware of the Celsius case, they were not familiar with the outcomes of implementing Total BIM. Therefore, the researchers began the workshop with a presentation of the preliminary interview findings from the Celsius case. The aim was to create a basic understanding of the Total BIM approach, which the reference group would later discuss in small groups. After these discussions, the reference group provided feedback on noteworthy findings and their own thoughts on potential overlooked findings. These discussions were analyzed from notes the reference group made during the workshop and used to refine the initial findings from the case. Following this first workshop, a brief questionnaire was distributed to the reference group to gauge their current understanding of BIM and their outlook on Total BIM. The questions were informed by the initial findings of the Celsius case study the responses primarily serving as a basis for shaping future workshops, site visits and discussions.

The second, third and fourth workshops were conducted alongside study visits to case projects with the reference group. Each of these workshops focused on discussing the implementation of Total BIM processes in the observed projects. The second workshop was conducted after the study visit to Glasblokkene Trinn 2 in June 2022, with 17 members of the reference group attending. For many of them, it was their first time observing Total BIM in practice. Therefore, the workshop discussions were focused on the observed implementation of Total BIM processes. The third and fourth workshops followed a similar structure to the second workshop. Both of these were conducted directly after study visits to the Lumi and SB47 projects in September 2022. The aim of these workshops was to explore the implementation of Total BIM by discussing observations from the projects studied. These workshops were attended by 17 members of the reference group.

A fifth workshop was conducted online, involving 25 members of the reference group, to discuss and explore the ongoing challenges when attempting to implement Total BIM. Held in June 2023, by this stage many of the reference group members had planned or already begun implementing Total BIM within their respective organizations. Consequently, they were well-positioned to provide feedback on my current research findings and contribute to discussions regarding the challenges they had encountered or anticipated when implementing Total BIM. These discussions were then considered during reanalysis of the interview data.

Additionally, another workshop was conducted in March 2023, involving sustainability and digitalization leaders from a large Swedish construction company, along with representatives from the CM company. This workshop had a specific focus on the CM company’s Lumi project, with discussions focused on how Total BIM could be applied to improve sustainability in renovation projects.

Although the data collected from the workshops is not directly presented in the findings, the discussions from the workshops provided insight into the current state of BIM in the construction industry, how Total BIM could be implemented, the challenges and benefits of implementing Total BIM. These discussions were triangulated with the interview and observation data to highlight significant empirical findings.

3.2.3 Site visits and observations

During this research project, three site visits were conducted to Total BIM projects. Lawrenz et al. (2003) suggest that the learning outcomes from site visits depend largely on the expertise of the visitors. Therefore, conducting the site visits with the reference group of construction digitalization experts provided me with rich data and insights into the applications of Total BIM. Two types of data were gathered from these visits. Firstly, I obtained firsthand data by observing the implementation of Total BIM in practice. Secondly, presentations were delivered by individuals involved in the projects, providing me with perspectives and insights from those most familiar with the implementation of Total BIM. The site visits and associated presentations were all filmed. Additionally, photographs were captured during the site visits to document noteworthy observations. Similar to the workshops, the findings from the site visits are not directly presented in the research findings but were triangulated with other empirical data collected to identify significant findings regarding Total BIM implementation. Furthermore, they were used to inform subsequent interview questions with representatives from the case study projects.

The first site visit occurred in June 2022 at the Glasblokkene Trinn 2 project. The visit began with presentations from the client, outlining how digital technologies supported the project strategy and how digital data were used for monitoring purposes. This was followed with a detailed presentation from a plumbing subcontractor, illustrating their use of Total BIM for planning, prefabrication, and on-site execution of their tasks. Additionally, I had the opportunity to visit the construction site and an early chance to compare the BIM representation on mobile phones with the actual construction progress. As previously mentioned, this project served as a background study for Total BIM. Conducting the site visit with the reference group provided me with an opportunity to observe their evolving perceptions of Total BIM and helped me to identify important Total BIM processes.

Two further site visits were conducted in September 2022. These site visits occurred at the CM company's ongoing projects, Lumi and SB47, and involved 17 members of the reference group. The first visit focused on the Lumi project, aiming to maximize material reuse with Total BIM. During this visit, the CM company demonstrated how they collaborated with designers to deliver production-oriented Total BIM and addressed the ongoing challenges related to quality control. Subsequently, I visited the construction site to observe the practical implementation of the Total BIM reuse processes. This included observing how materials were dissembled, stored, tagged, and later assembled using Total BIM. These observations provided insight into how Total BIM facilitates the integration of technologies to achieve sustainability objectives.

During the third site visit to SB47, the CM company demonstrated that in renovation projects, Total BIM must not only account for the new construction but also contain information regarding which structures to preserve and demolish. Therefore, the site visit contributed to a deeper understanding of the challenges associated with Total BIM in renovation projects. Additionally, I observed how the CM company worked with information during the design phase to ensure structured, accurate and trustworthy information for construction workers, thereby enhancing my understanding of the processes required to implement Total BIM project in all project stages.

3.2.4 Miscellaneous data

Additional data were collected through a review of internal company documentation, company presentations, informal discussions, observations made via on-site BIM platform access, and seminars. The internal company documentation included materials such as the "BIM strategy" for the Celsius project, published by the CM company in 2017. Document analysis is valuable for covering events that span a long period (Yin, 2009). In this context, analyzing the strategy document helped understand how the Total BIM approach evolved from the beginning of the project to completion, highlighting important findings from the case.

This evaluation process was further supported by company presentations that described Total BIM projects and processes, along with my firsthand observations from accessing the Lumi and SB47 projects on-site BIM platform. Accessing this platform provided me with an opportunity to capture real project data and observe how BIM, communication, and construction evolved over time. I regularly monitored the platform to capture data, such as communication, checklists, filters and screenshots, which formed an important part of the empirical data collected during this study and were used to present findings from real-world cases.

In addition, two seminars were organized with the CM company's project managers to collect real-world examples of how they implemented Total BIM processes on construction sites. These seminars differed from the workshops in that I presented what I had identified as the key on-site Total BIM processes. I then directly asked the two project managers to provide concrete examples of their implementation in the Celsius, Nattugglan, Lumi and SB47 projects. These examples were then used to gather real project data from the on-site BIM platform, which is subsequently presented in the findings.

3.3 Data analysis

In this study, I conducted a thematic analysis on the interview transcripts. Thematic analysis is a widely used method for analyzing, organizing and reporting themes in qualitative data (Braun and Clarke, 2006). Conducting a thematic analysis is a recursive process, that goes back and forth throughout the various phases of analysis (Braun and Clarke, 2006). Braun and Clarke (2006) identified six phases of thematic analysis, which were applied in this research. These phases included: (1) I began by transcribing the interviews. For some of the early interviews that were not transcribed, detailed summaries were made. I then familiarized myself with the data by reading through the transcriptions and making initial notes. The workshops and observations conducted with a reference group of industry experts supported the process of highlighting important use cases of Total BIM implementation. This empirical data enabled me to (2) generate preliminary ideas about themes of the interviews that I found most relevant to each study, and I began sorting the data (sections of text in the transcripts) according to these themes. An example of this process emerged during the site visit to Glasblokkene Trinn 2, which the CM company attended as part of the reference group, I observed how checklists could be integrated with scheduling tools to control the completion status of construction activities. (3) Potential themes became more focused as I began categorizing the data into main themes and sub-themes. I moved back and forth between the interview transcripts, the workshop and observation data, and the background studies conducted as part of this research. During this process, I aimed to identify findings from the interviews that demonstrated how Total BIM overcomes some of the challenges associated with traditional BIM implementation. This process led me to (4) review and refine the themes further, and it was repeated until (5) a clearer definition of the themes emerged. For example, in Paper II, a review of existing literature highlighted issues relating to extracting measurements from BIM on construction sites. The empirical data collected during this research provided examples of how Total BIM was implemented to overcome these challenges, such as the use of new user-friendly software designed for use on construction sites. Therefore, this emerged as a main theme. Additionally, during this process of analysis, unexpected themes emerged, where it became evident from the interview data that Total BIM contributed to improving communication for site workers, which was possible to connect to sub-themes such as controls, checklists, scheduling, and integrated issue management. The identification of themes within each study formed a base for the (6) structure and writing of the different papers.

In Paper I, I adopted a slightly different process in the identification of themes. The interview questions were specifically designed around themes outlined in an existing BIM framework (Bosch et al., 2016; Sundquist et al., 2020). This framework contained four main themes, each with two sub-themes, and served as a starting point to explore Total BIM as a novel approach. The interviewees possessed experience in both traditional BIM and Total BIM projects. Consequently, the interview questions aimed to highlight the differences between these two types of projects, with the CM company’s overall approach of Total BIM implementation as the focus of the study. However, in my opinion, the responses provided by the interviewees did not always align precisely with the outlined themes. Hence, by continuously analyzing the interview transcripts, I first sorted the data into the main themes (Ecosystem, Strategy and Innovation, Organizing, and Technology), then into the eight sub-themes, and finally into unique findings within these sub-themes. The findings in Paper I are structured and presented according to the themes in the existing BIM framework.

The process of moving back and forth between the interview transcripts, workshop discussions and observation data is exemplified in the following scenario: During the site visit to Glasblokkene Trinn 2, which was also attended by the CM company as part of the reference group, I observed the visualization of BIM data for monitoring construction site progress. This theme was discussed in the workshop that followed, with a particular emphasis on integrating checklists into the on-site BIM platform. Subsequently, I observed that the CM company had begun visualizing safety issues from communication data and implemented controls for BIM objects using checklists. These observations were also reflected in the interviews, and a comparison of the empirical data highlighted how Total BIM is still an evolving approach, which enables new possibilities to integrate processes.

4 Summary of the papers

This chapter highlights the main aims, data collection methods, findings and contributions from each of the four papers.

4.1 Paper I

Embracing BIM in its totality: a Total BIM case study

Disney, O., Roupé, M., Johansson, M., & Domenico Leto, A. (2022). Embracing BIM in its totality: a Total BIM case study. *Smart and Sustainable Built Environment*.

Aim

This paper investigated the processes and outcomes of implementing a Total BIM approach as the single source of information in all phases of an office and laboratory construction project.

Data collection

The data for this case study were collected through nine semi-structured interviews, informal discussions with key actors and document analysis from the case company, including presentations and BIM manual.

Findings

Findings show how the Total BIM approach enabled the use of a single source of information, thereby addressing delays and errors commonly associated with the production and use of 2D paper drawings. Although many of the processes implemented in the project were not new, the benefits were realized by combining them. Four main factors critical to the successful implementation of Total BIM were identified: BIM as the legal and contractually binding construction document; high-quality, production-oriented, cloud-based BIM; modern hardware and software enabling BIM use by construction workers on-site; strong leadership and management.

Contributions

This paper contributes to advance the existing body of knowledge on model-based construction processes and BIM by identifying critical factors for implementing the Total BIM approach. Notably, the research uncovers new work processes where construction workers independently created and extracted construction information directly from BIM.

4.2 Paper II

Total BIM on the construction site: a dynamic single source of information

Disney, O., Roupé, M., Johansson, M., Ris, J., & Höglin, P. (2023). Total BIM on the construction site: A dynamic single source of information. *Journal of Information Technology in Construction (ITcon), 28(27), 519-538*.

Aim

This paper extends on Paper I by focusing on three additional projects and explored how Total BIM was used throughout a construction project as the dynamic single source of information, specifically focusing on how Total BIM was implemented and used on construction sites.

Data collection
Data were gathered from interviews, observations from site visits, workshops, and seminars, focusing on four projects: three commercial projects from a Swedish construction management company Celsius, Lumi, SB47 and one hospital project from Norway called Glasblokkene Trinn 2.

Findings
Findings highlight the key Total BIM processes for a dynamic single source of information on construction sites. The implementation of these processes enabled users to create and extract construction information from the on-site cloud-based BIM platform. Furthermore, the findings demonstrate how these new work processes impacted users throughout the entire construction process, necessitating a shift in mindset from traditional projects.

Contributions
This paper addresses a gap in research related to real-world model-based construction projects and provides concrete examples of how Total BIM was and can be implemented on construction sites as a dynamic single source of information. Furthermore, it is argued that Total BIM addresses many of the limitations found in previous state-of-the-art BIM projects and enables new opportunities for efficient data management.

4.3 Paper III

Driving circularity with Total BIM: an integrated approach to data-driven design

Disney, O., Roupé, M., & Johansson, M. (2023, September). Driving circularity with Total BIM: an integrated approach to data-driven design. *In Proceedings of the 39th Annual Association of Researchers in Construction Management Conference (ARCOM), 2023, Leeds, United Kingdom*

Aim
This paper explores how new sustainability regulations may drive the implementation of Total BIM and investigates how an informed data-driven approach can lower carbon emissions by supporting increased material reuse in construction projects.

Data collection
This paper draws on data from a case study of an ongoing renovation project. The data consists of interviews, workshops, and observations from a study visit to the Lumi project.

Findings
Findings show a novel digital process for increasing material reuse in construction renovation projects. Disassembled materials were tagged and logged in a database. The materials that best matched the intended design had their unique product identifier inserted into BIM. Site workers then used this information during construction to place the reused materials in the intended locations. The study shows how the client, project managers, and tenants were able to lower the project’s carbon emissions by making informed, data-driven decisions based on the implementation of Total BIM.

Contributions
This paper offers a leading empirical example of how Total BIM can efficiently address the upcoming tough sustainability requirements by using informed and accurate digital sustainability data. Furthermore, the paper highlights ongoing challenges, such as accessibility regulations and incentives, which may restrict reuse options.

4.4 Paper IV

Digital disruption in the construction sector: going all-in with Total BIM
Duman, D.U., Disney, O., Roupé M., Johansson, M., & Claeson-Jonsson, C. Digital disruption in the construction sector: going all-in with Total BIM. *Work in progress paper.*

Aim
Using a disruptive innovation theoretical lens, this paper investigates whether the effects of implementing Total BIM create digital disruption and if Total BIM is the digital disruption that the construction industry would need to address performance and productivity issues.

Data collection
This paper draws on data from six semi-structured interviews with five representatives from the four project cases, Celsius, Nattugglan, Lumi and SB47, and one representative from a technology company. Additional data were gathered from information discussions, workshops, and observations from site visits to two ongoing projects.

Findings
Findings illustrate the digital, disruptive and innovative properties of Total BIM. In this study the properties were interconnected and mutually trigger one another. The combination of these effects created a digital disruption that can potentially address performance and productivity issues within traditional business processes and practices in construction projects.

Contributions
This paper contributes by exploring the outcomes of implementing Total BIM and underscores the importance of establishing an innovative culture. Furthermore, the paper provides evidence that even smaller companies can leverage digital transformation capabilities, and it is not limited to larger, established ones.

5 Discussion

Drawing on empirical data from pioneering real-life projects, the aim of this thesis was to explore how Total BIM was implemented as a single source of information for construction workers thus overcoming the limitations of working with traditional 2D drawings. To date, there has been a lack of empirical evidence and of studies focusing on model-based construction (Brooks et al., 2023). This study contributes by highlighting findings from three completed and two ongoing Total BIM projects. An analysis of the qualitative data – including interviews, site observations, and workshops with practitioners – showed that not only is it possible for construction workers to use Total BIM, but there were indications that it may even become the preferred way of working. In this chapter, the main findings from the studies are discussed.

The studied cases demonstrate that it has in fact been possible to implement Total BIM. Previously, construction workers encountered challenges such as trusting the data-quality in BIM (Jaskula et al., 2024; Perera et al., 2023) or using software that was never intended for model-based construction (Aune, 2018; Budarina, 2017; Rybus, 2022; Trafikverket, 2013; Ulvestad and Vieira, 2021). When such problems arise, there has been a tendency, or it may have been necessary, to resort to using traditional 2D drawings. However, what was observed in the Total BIM projects was that these challenges were overcome by setting BIM as the legally binding source of information rather than 2D drawings, and therefore developing the BIM to a higher standard than in traditional projects (Paper I, II and IV). Furthermore, this approach was supported by new user-friendly software, designed for BIM use on construction sites (Paper II). These factors enabled construction workers to fully utilize the Total BIM approach and model-based processes. The findings show how Total BIM helped realize value in projects that has not previously been possible, such as informed data-driven decision-making with climate data to improve sustainability (Paper III). Furthermore, implementing Total BIM can accelerate the digital transformation of the construction industry, which can require stakeholders to adopt new technologies, methods, and processes (Paper I, II and IV).

As mentioned earlier in this thesis, despite studies indicating that BIM use is increasing (Bosch-Sijtsema et al., 2017; NBS, 2023), it is important to recognize that using BIM means different things to different people (NBS, 2023). Different understandings will no doubt also occur with Total BIM (Cousins, 2017) and model-based construction processes (Brooks et al., 2023), especially due to the limited number of implementation attempts in practice and consequently limited research of empirical examples (Brooks et al., 2023). The research findings in this thesis address this gap in knowledge by providing empirical evidence from real-world case studies, demonstrating the implementation of Total BIM and how it mitigates fragmentation issues (Fisher et al., 2017; Samuelson and Stehn, 2023; Sacks et al., 2018) by integrating information and communication within a common platform on construction sites (Paper I, II, III and IV). Hence, the totality of the approach to BIM. Total BIM is an "all-in" approach to BIM throughout the design and construction phases of projects, which may be the answer to leveraging the benefits outlined in early stages of BIM development (Azhar, 2011). Furthermore, it builds on the principles of IPD and VDC (Fisher et al., 2017), aiming to improve collaboration and contribute to a new way of thinking about BIM, as shown by early contractor involvement in Total BIM design reviews (Paper II).

The findings in this thesis identify four main processes critical for implementing Total BIM on construction sites (Paper II): dynamic views, sections and measurements; filtering and quantity take-off; controls and checklists; production-oriented information. Construction workers must be able to easily navigate BIM software to display information necessary to perform their activity, such as creating views, sections and measurements. They must also have access to user-friendly information filtering options, which helps avoid problems of information overload (Anderson et al., 2012) and can be used to plan construction activities. One method of simplifying filtering was the CM company's implementation of the "Press here" function, which drew construction workers' attention to the most important construction information in one single digital tab (Paper II). This contrasts with many previous projects that attempted to implement model-based construction using software intended for designers rather than for construction workers (Aune, 2018; Budarina, 2017; Rybus, 2022; Trafikverket, 2013; Ulvestad and Vieira, 2021). The result was that the software intended for expert users made it difficult for construction workers with limited digital capabilities to find the information they needed. Moreover, the development of new software specifically intended for use on construction sites enabled construction workers in Total BIM projects to easily create and understand the views needed, the relevant measurements and the filters, rather than having to rely on experts to do it for them (Budarina, 2017; Trafikverket, 2013). The successful implementation of these processes has further generated implementation of additional processes, including controls, checklists and requests for information (RFIs), which benefit from integrated information (Paper II). By integrating information in a common platform, data and information were generated and stored in a structured format during the construction phase, as opposed to the disparate and unstructured information sources found in traditional projects, such as e-mails and paper documents. Consequently, construction workers not only consumed information, as in traditional projects, but also actively produced and disseminated structured information during the construction phase. However, it is important to note that these processes and the construction site software must be easily accessible and user-friendly (Anderson et al., 2012) otherwise it is difficult for construction workers to understand how it benefits them, and they may want to revert to traditional ways of working (Paper IV).

By connecting these dynamic processes on construction sites in a single digital platform (BIM) as has been done in the projects studied, it becomes the single source of cloud-based information, providing construction workers with the necessary features to perform their work (Paper II). Hence the choice of the metaphorical label "Total BIM" signifies the self-sufficiency of the "new" BIM as opposed to the conventionally used (traditional) BIM. The totality of this model-based approach to construction compels designers to focus resources on BIM development rather than addressing problems associated with producing and maintaining parallel sources of information as in traditional projects to compensate for the deficiencies in BIM (Aibinu and Papadonikolaki, 2020). In a Total BIM project, BIM is much more than merely a coordination or visualization tool (Bosch-Sijtsema et al., 2017; Sacks et al., 2018; Tu et al., 2023). It provides a structure for connecting data and information to objects, which is now supported empirically in this thesis.

In projects where traditional drawings are legally binding, BIM tends to not be actively used due to a lack of trust as the data quality is not consistently maintained (Anderson et al., 2012; Jaskula et al., 2024). The findings in this research highlight that maintaining data quality is still a challenge in Total BIM projects as design firms lacked data quality assurance processes (Paper II). In a Total BIM project, the goal is for construction workers to have a single dynamic source of information. Therefore, the quality of data and information contained within BIM are essential. In the Norwegian hospital project, a systematic process was implemented to ensure the quality of BIM using the 17-week, 7-step approach (Paper II). This step-by-step approach integrates construction worker expertise into the design phase to optimize and ensure the completeness and constructability of a BIM's given control zone (or

Takt zone) before construction begins. It builds on the VDC approach described by Fisher et al. (2017), where early contractor involvement aims to improve information quality. However, unlike traditional projects, in Total BIM projects, the aim is to improve BIM for use during the construction phase. Therefore, while design firms may lack the necessary quality assurance processes for Total BIM, one potential solution may be to integrate the expertise of construction workers into the final stages of quality assurance during the design phase (Paper II). It is worth noting that the 17-week, 7-step process represents just one approach to structuring the final stages of the Total BIM development. Other organizations adopting a similar approach may have a different number of weeks or steps based on their specific requirements.

In the current study, the collaboration between designers and construction workers was extended into the construction phase (Paper I, II and IV). Construction workers created RFIs within the BIM platform, containing structured information such as a description of the request, photographs and corresponding location in BIM. This approach allowed designers to resolve issues faster compared to traditional projects reliant on less structured communication sources (Paper IV). In the projects studied, communication through an open platform facilitated streamlined and efficient communication, which contributed to construction workers moving away from traditional methods and towards adopting Total BIM (Paper I and II). Jaskula et al. (2024) noted that in traditional projects, communication regarding BIM issues often occurs through unstructured channels such as emails, resulting in multiple sources of information and leading to mistakes and omissions due to the of integration. Furthermore, Brooks et al. (2023) found that project teams become more coordinated by communicating with a single source of information. Therefore, the findings in this thesis support these claims and provide empirical evidence from real-world projects that integrating construction information with communication is essential for realizing the benefits of Total BIM.

In my view, Total BIM extends beyond merely model-based construction; it entails the digital transformation of construction processes to unlock new opportunities for value creation. An illustrative example of this was the use of connected data to make informed, data-driven decisions on sustainability (Paper III). In order to align with EU sustainability objectives, Sweden is enforcing climate declarations, although implementation has so far been somewhat limited due to unspecified maximum values (Paper III) (Sadri et al., 2022). In traditional projects, producing climate declarations is both costly (Zheng et al., 2023) and lacks representative data specific to the project, often relying on generic climate data instead (Sadri et al., 2022). However, in the study of an ongoing Total BIM project (Paper III), objects are linked to data regarding properties such as weight, material type, and the presence of recycled materials. This approach facilitated the generation of climate reports, enabling a more frequent and accurate understanding of the building’s climate impact, which in turn informed data-driven decisions aimed at reducing the climate impact of the building. Consequently, as climate regulations continue to evolve and become enforced, information-rich BIM, as seen in Total BIM projects, has the potential to reduce the effort of calculating climate emissions (Hollberg, 2020). Nevertheless, an ongoing challenge remains a tradeoff between efficiency and accuracy (Zheng et al., 2023). In the studied project (Paper III), design teams were tasked with adding more data to objects than is common in traditional projects. Therefore, while the Total BIM approach produced reliable and realistic data, its efficiency can be questioned. However, with increasingly tougher climate requirements, such an approach might ultimately become necessary.

The findings also highlighted new monitoring and analysis opportunities within and between construction projects (Paper I, II and III). While the creation of RFIs and checklists are not novel activities, the innovation lies in the way they were integrated within a single BIM platform alongside the other Total BIM activities such as measuring and filtering. The benefits of such integration were observed when live data from RFIs concerning safety issues were visualized as colors in a "traffic light" on screens around the construction site (Paper II). Visualizing dynamic safety warnings in action, which was not possible using paper-based reports, motivated construction workers to address risks promptly, thus restoring the "traffic light" to amber or green, and thereby contributing to increasing overall safety (Paper II). Therefore, the case study evidence shows how Total BIM and the involved model-based construction processes enable improved data analysis and contribute to more informed, data-driven decision-making (Brooks et al., 2023).

Based on the rich empirical data of this study, it has been shown that Total BIM transformed the way work was performed on construction sites. However, during the initial implementation of Total BIM, challenges arose in finding software with adequate BIM measuring tools (Paper I and IV), which has been identified as a major obstacle in previous studies (Aune, 2018; Budarina, 2017; Rybus, 2022; Trafikverket, 2013; Ulvestad and Vieira, 2021). Previously, the lack of user-friendly software designed for construction activities might have been misconstrued as a lack of digital competence among construction workers (Budarina, 2017; Mershbock and Nordahl-Rolfsen, 2016; Rybus, 2022). During the design phase of the first project undertaken by the CM company, managers became aware of and subsequently implemented new software that was being specifically developed for model-based construction activities. This software has been used in all the cases studied here and the findings clearly show that with user-friendly software, construction workers are fully capable of applying model-based construction processes. Furthermore, when they understood how it benefited them, many expressed a preference for this way of working (Paper I, II, and IV).

In the studied projects, the construction site software enabled workers to seamlessly transition between 2D and 3D perspectives, thereby enhancing their understanding of their work and improving navigation within the model. This use enabled construction workers to realize the benefits from both 2D and 3D perspectives (Paper II). Consequently, a Total BIM project might be considered "drawingless," while still affording construction workers the flexibility to view information in a format like digital drawings. The key distinction lies in the fact that construction workers themselves generate views and measurements, as opposed to designers doing it. The need for construction workers to create their own POVs was identified as an area of improvement in the Röfors bridge project as early as 2013 (Trafikverket, 2013), and now has now been realized through Total BIM. Furthermore, Total BIM enables construction workers to create POVs and measurements that they need, rather than relying on those that designers believe they need (Paper II). However, some challenges remain. For instance, modeling objects like electrical cables proved difficult for designers due to software limitations and the flexibility of electrical installations, so they were instead presented on large PDFs (Paper I), which resembles working with "static" or "dead" documents that often lead to errors (Brooks et al., 2023; Gaunt, 2017; Van Berlo and Natrop, 2015). This challenge highlights the need for continued software and process development to ensure that construction information can be generated from the "live" BIM and displayed in desired format for end-users.

The research findings suggest impacts on the bidding process for subcontractors (Paper I and IV). Subcontractors interested in bidding on the project received IFC files and quantity lists extracted from BIM. Despite initial concerns regarding the potential exclusion of firms with limited digital capabilities, this approach resulted in more bids, with bids being more evenly distributed (Paper I and IV). Contrary to concerns expressed in previous studies that small firms may be excluded from high-end BIM projects (Dainty et al., 2017), the findings suggest that Total BIM may increase participation of small firms. This might be attributed to the simplified, transparent, and cost-effective nature of the bidding process, making it more feasible for small firms to engage in bidding on the project. For example, in the Lumi project, information specifying which wall surfaces were within five meters and perpendicular to windows letting in daylight was added to BIM. These surfaces require more time from painters to conceal imperfections, consequently impacting costs and the bidding process. However, it is essential that the approach to bidding remains flexible, especially if firms are hired before the finalization of the design, as occurs in the 17-week, 7-step process (Paper II), which may necessitate adjusting costs accordingly later in the project.

During this research process, possible biases may have influenced discussions held during the site visits and workshops, especially as most participants in the reference group held roles related to digitalization within their respective organizations. It is also possible that the interactions I had during these discussions were influenced by the desired changes of the individuals involved, possibly steering me towards certain findings. For instance, the CM company openly expressed that implementing Total BIM would become easier if other organizations followed suit, as companies they work with would become more familiar with Total BIM processes. Consequently, it was in their best interest to highlight the positive outcomes of adopting Total BIM. However, to mitigate potential biases a third social-science-oriented and qualitative researcher joined my supervisory team. My third thesis supervisor had no prior relationship with any members of the reference group and was not a “BIM” researcher. Furthermore, access to the on-site BIM platform in two of the CM company’s projects enabled me to validate research findings by monitoring ongoing communication, checklists, and object information. Additionally, I tested the work-in-progress and preliminary findings at conferences such as CONVR and ARCOM over the last few years, where they were discussed and challenged by a broader audience of researchers.

6 Conclusions

This research has addressed a gap in knowledge by providing empirical data from real-world pioneering case studies of Total BIM projects. The findings have shown the feasibility of implementing Total BIM and overcoming the hardware and software issues that have so far limited previous state-of-the-art BIM projects (Aune, 2018; Bråthen and Moum, 2016; Budarina, 2017; Cousins, 2017; Davies and Harty, 2013; Mershbock and Nordahl-Rolfsen, 2016; Rybus, 2022; Trafikverket, 2013; Ulvestad and Vieira, 2021). Total BIM is an “all-in” approach that aims to embrace BIM in its totality (Cousins, 2017), leveraging the benefits of a single source of legally binding information from design to construction, thus eliminating the parallel production of 2D drawings. By eliminating the production and maintenance of paper-based information sources, where inefficiencies and errors are common, Total BIM offers an opportunity to unlock value previously unobtainable in traditional projects. However, realizing the full potential of Total BIM requires more than just implementing model-based construction processes; it necessitates a shift in mindset regarding BIM implementation.

This thesis has taken the first steps at defining Total BIM and highlighting the model-based construction processes that are required for successful implementation. By using new user-friendly software designed for construction sites, workers transition from using “static” 2D drawings, to a “live” dynamic cloud-based BIM, thereby assuming a proactive role in generating structured information during the construction phase. This shift empowers the construction workers to create the information they require, rather than relying solely on information that designers provide them with. Furthermore, this thesis has shown that integrating construction information within the on-site BIM platform, along with other features like RFIs and checklists, creates new opportunities for site monitoring and analysis. Additionally, Total BIM may be necessary to efficiently address upcoming tough sustainability requirements, as traditional approaches lack representative data and can be costly. The findings demonstrate the use of Total BIM for increasing material reuse in renovation projects by integrating sustainability data into BIM. This integration enabled stakeholders to make ongoing informed, data-driven decisions to reduce carbon emissions.

This study has demonstrated several positive outcomes of Total BIM implementation for practitioners. It has shown that Total BIM can improve working conditions such as safety and constructability for construction workers. Moreover, despite concerns that high-end BIM projects exclude small firms (Dainty et al., 2017), this study found that Total BIM may increase the participation of small firms due to the simplified bidding process for subcontractors. Subcontractors were provided with quantity lists from BIM, thus alleviating the need to allocate resources toward manual calculations, which resulted in more bids and more evenly distributed bids. Additionally, the study indicates that construction workers possess sufficient competencies to work with Total BIM and even prefer it as they found communication to be more streamlined. Nevertheless, it is important to acknowledge ongoing challenges. The findings indicated that designers lack quality assurance processes for Total BIM projects, where the BIM, rather than drawings, is legally binding. Furthermore, if subcontractors are expected to be involved in the final design stages, as with the 17-week, 7-step process, it requires a change in current practices. Therefore, despite BIM not transforming the construction industry as previous studies have suggested it would, Total BIM may hold the potential to deliver the required digital disruption. However, its success is currently heavily reliant on the expertise and leadership skills of those implementing the change.

6.1 Suggestions for future research

Although this thesis has taken the first steps to provide practitioners and researchers with insights from real-world Total BIM projects, there remains much to explore. Primarily, I have focused on the implementation of Total BIM in the construction phase. Therefore, a promising avenue for future research lies in exploring how Total BIM impacts architects and engineers, and how it alters design processes compared to traditional projects. For instance, during this study, I was informed that design teams lacked quality assurances processes for Total BIM projects. If indeed these processes are lacking, then what quality assurance measures are necessary for Total BIM projects, and how could they be implemented?

The findings from the Norwegian hospital project highlighted the 17-week, 7-step process, where construction worker expertise is involved in the final stages of the design for a given control area. Future research should explore how to best structure the number of weeks and steps depending on the size and complexity of the activities involved in the control area, while also considering the perspectives of those involved. Moreover, this research has found that Total BIM aims to resolve constructability issues during the design process. In traditional projects, design teams may have focused on the building's design without being fully aware of or prioritizing constructability issues. However, in Total BIM projects, it becomes easier to understand constructability issues due to the final representation of construction information being in 3D. Nevertheless, this research has not addressed how design teams are expected to solve these challenges or how they experience new expectations placed upon them. Therefore, it would be interesting for future studies to explore how constructability issues can be resolved during the design phase and what processes are necessary to implement.

Implementing Total BIM as a single source of information during the construction phase establishes a structure for generating and storing data. The findings presented in this thesis demonstrate not only the use of data by construction workers but also their creation of structured data. This study provides some early practical examples, illustrating how Total BIM has been used to improve performance, such as by visualizing RFIs related to safety on screens located across the construction site. Total BIM offers significantly greater data analysis opportunities than were previously feasible in traditional projects (Brooks et al., 2023). Consequently, I argue that there exists much unexplored potential to increase monitoring and analysis of construction sites, now made possible by Total BIM. One potential area for future research could be exploring how checklist data in Total BIM projects could improve efficiency. For instance, it could be integrated with scheduling tools, used to visualize and monitor progress, or enable performance comparison across projects within an organization. This study has also shown how Total BIM facilitated informed, data-driven decision-making to achieve sustainability goals. A similar approach could be used to guide ongoing cost decisions throughout projects, an aspect that remains unexplored but could be facilitated by Total BIM. Additionally, this study highlights how Total BIM projects prioritize managing data over documents. However, research has not yet explored how to efficiently manage the flow of data in Total BIM and model-based projects. Therefore, future research could explore the data and information requirements for Total BIM projects, potentially facilitating its adoption and the development of new standard practices for Total BIM.

Finally, it is worth mentioning that when I began this research, I was aware of only one construction company in Sweden that was actively working with Total BIM. However, during the workshops conducted throughout this study, I have observed that many members of the reference group are now beginning to implement Total BIM within their respective organizations. This development is encouraging and can support the development of new findings regarding Total BIM.

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