Total BIM in Practice: A dynamic single source of information on the construction site

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TOTAL BIM IN PRACTICE: A DYNAMIC SINGLE SOURCE OF INFORMATION ON THE CONSTRUCTION SITE

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ABSTRACT: *The rapid advancement of digital technologies presents the construction industry with opportunities to change how site work is performed. Traditionally site work has been dominated by taking information from static construction documents such as 2D paper drawings. However, recently in the Nordic region a dynamic approach known as Total BIM has gained interest. Total BIM is an approach where BIM replaces 2D drawings as the contractual and legally binding construction document, cloud-based production-oriented BIM and powerful mobile BIM-viewers are used on-site. By having a dynamic single source of information site workers face new demands as they extract construction information directly from BIM themselves. Instead of using static 2D drawings they interact dynamically with BIM on mobile devices, changing the process of how work was implemented on the construction site. This paper is based on four real-life case studies, site visits, workshops and semi-structured interviews. Key digital Total BIM features are investigated that site workers use to perform the new work methods, including measuring, filtering, visualizing, communicating, checklists, and requests for information. These lead to a more dynamic construction process where the mobile BIM-viewer software becomes a central communication and management platform. This paper highlights the opportunities of working with dynamic Total BIM over static 2D drawings that can be used for implementing Total BIM strategy on the construction site. Furthermore, this paper addresses issues commonly found in state-of-the-art BIM projects and contributes practical concrete examples of on-site Total BIM use.*

KEYWORDS: *Total BIM, digitalization, Building Information Modeling, BIM on-site, drawingless construction*

1. INTRODUCTION

How could BIM (Building Information Modeling) be used throughout a construction project as the dynamic single source of information on the construction site, i.e., Total BIM? Although research has shown benefits of using BIM in construction projects (Azhar, 2011; Sacks et al., 2018), we lack examples of empirical cases that successfully use BIM as a dynamic single source of information in the construction phase. Furthermore, research concerning BIM implementation in the construction phase is scant (Tu et al., 2021).

To date, BIM is mostly used in the design phase for coordination and clash detection (Eadie et al., 2013; Tu et al., 2021), but for the construction site focus shifts towards producing 2D documentation, and consistent updating of BIM ceases (Van Berlo and Natrop, 2015). When BIM is not updated consistently, it no longer accurately reflects what is to be built; therefore, trust in BIM is lost, and it cannot be used effectively on-site (Påsse et al., 2022). This occurs due to a lack of demand for BIM, which means that designers focus on delivering 2D drawings as in most countries they are legally obliged to do so (Ghaffarianhoseini, 2017; Tu et al., 2021). The parallel processes of creating both 2D drawings and BIM are also costly and lead to errors (Disney et al., 2022a).

Currently, Total BIM is understood as an approach where BIM is "embraced in its totality" (Cousins, 2017; Disney et al., 2022a). In a Total BIM project, BIM is used throughout all project phases as the single source of information; it is the legally and contractually binding document; and information is accessed from the cloud (Disney et al., 2022a). In the construction phase, site workers themselves use BIM on mobile devices to create and extract all the construction information (e.g., measuring, object information, views and sections) they need to carry out their work. Total BIM sets new demands on project stakeholders and has only recently become possible due to advancements in hardware, software and connectivity.

This article investigates four case studies where Total BIM has been implemented as the dynamic single source of information on-site. Key Total BIM features that are implemented for site workers and management to achieve on-site construction without requiring 2D static drawings are highlighted. This study can provide insight and strategies for researchers and practitioners regarding how Total BIM can be successfully implemented in the construction phase as a dynamic single source of information.

2. ON-SITE LIMITATIONS IN PREVIOUS STATE-OF-THE-ART BIM PROJECTS

The idea of using BIM on the construction site is not new (Bråthen and Moum, 2016). Various attempts have been made throughout the last twenty years to bring digital design information to the construction site (Bråthen and Moum, 2016; Davies and Harty, 2013; Johansson and Roupé, 2019). These attempts have been made using tools such as virtual reality, BIM kiosks, laptops, tablets and smartphones. However, as highlighted in the examples below, implementation on-site has been rather limited. These limitations are sorted and discussed chronologically, in relation to the incremental development and maturity of the technology over the last decade.

The 2013 Roförs bridge project in Sweden was a unique project where work on-site was expected to occur directly from BIM by viewing and extracting information from BIM on tablets. Due to limitations at the time with BIM-viewer software site workers were unable to extract measurements and specific construction information on mobile devices. A structural engineer was needed on-site to create Production-Oriented-Views (POVs) (Johansson and Roupé, 2019). These POVs were screen captures from BIM with measurements, dimensions and object information attached. The initial aim was not achieved as the screenshots were not interactive.

In the 2016 Norwegian Urbygningen project, the refurbishment of a building at the Norwegian University of Life Sciences, BIM kiosks were used as it was found that 2D drawings do not provide sufficiently detailed information on-site (Bråthen and Moum, 2016). Static BIM kiosks were placed on each floor of the building with wired internet connections and large TV screens to display BIM in the Solibri software. Implementing BIM in this way on-site helped workers with visualization, planning, coordination and provided them with a better, more up to date flow of information from design to the construction site (Bråthen and Moum, 2016). However, the main purpose of the BIM kiosks was purely for visualization and not used to carry out the work. Additionally, the BIM kiosks were placed in static locations due to their size and not able to be used directly where work occurred.

The 2017 Oslo Airport Terminal 2 project was the construction of a new terminal building. It was estimated that 50 000 paper drawings and documents would be needed to facilitate reinforcement work. Due to the complexity of the project, it was decided to use BIM instead (Mershbock and Nordahl-Rolfsen, 2016). By having all "drawings" accessible in one place (using the Tekla BIMsight software on iPads) it was more convenient and easier than having to make sense of searching through multiple sets of paper drawings (Mershbock and Nordahl-Rolfsen, 2016). On-site BIM use in the project was limited to reinforcement work. Mershbock and Nordahl-Rolfsen (2016) describe practical on-site BIM use in the construction industry as rare due to challenges with standard contracts as well as limited IT resources and capabilities.

The ongoing Slussen project in Stockholm is the rebuilding of a large lock to create a new pedestrian friendly urban quarter. The project aimed to be delivered 100% digitally eliminating the need for over 15 000 paper drawings (Cousins, 2017). However, some early work in the project still used 2D printed drawings. It was recognized by the BIM strategist for the city of Stockholm that traditionally in large projects a huge effort is needed to make drawings look good, most of which are never used (Cousins, 2017). Instead, the aim in the project was to work digitally, to enable staff to focus on solving technical design issues rather than creating drawings. The plan was to use BIM kiosks and virtual reality on-site, supported by printed views from BIM. BIM was the legally binding construction document rather than traditional 2D drawings. However, construction teams had to resort to surveyors using "total stations" to exactly place structural elements on-site because the software did not function effectively for users to take measurements.

Two separate Norwegian hydropower plant projects, SMISTO and Vamma 12, both completed in 2019 aimed to be delivered without drawings. Despite it being possible for site workers to create their own POVs, designers in the project created predefined ones with attached dimensioning to facilitate construction (Budarina, 2017). Reasons given by Budarina (2017) include the lack of BIM competencies on-site and the lack of software tailored for on-site use. It was also found that the Solibri software used in the project for viewing the model may be more suitable for skilled users (Budarina, 2017). In another Norwegian hydropower plant project, Nedre Otta completed in 2020, BIM kiosks were implemented. This project used Autodesk Navisworks and similarly to the other hydropower plant projects SMISTO and Vamma, it was found that the software did not function effectively for taking exact measurements on-site (Aune, 2018). There were also ambiguities with information on objects such as quantities and total length (Aune, 2018).

A recent winner of the Tekla Global BIM awards in 2020 for best BIM project, the Norwegian Randselva Bridge is the longest bridge built without drawings to date (Rybus, 2022; Ulvestad and Vieira, 2021). Instead of delivering traditional drawings the project focused on delivering BIM by transferring data through IFC files, which was viewable on-site in Solibri (Rybus, 2022). Many benefits were reported including that it may even be the preferred way of working (Ulvestad and Vieira, 2021). However, similar issues to the projects described above were also encountered. Without good BIM-viewer software it was hard to filter and extract the required data and software was not optimized to present section views from BIM with relevant information (Ulvestad and Vieira, 2021). These challenges led to users on-site taking 3D screenshots at BIM stations then adding information and descriptions manually (see FIG. 1) (Rybus, 2022; Ulvestad and Vieira, 2021). Bad weather conditions also meant that these would often need to be printed on paper and laminated rather than used on iPads as preferred (Ulvestad and Vieira, 2021).

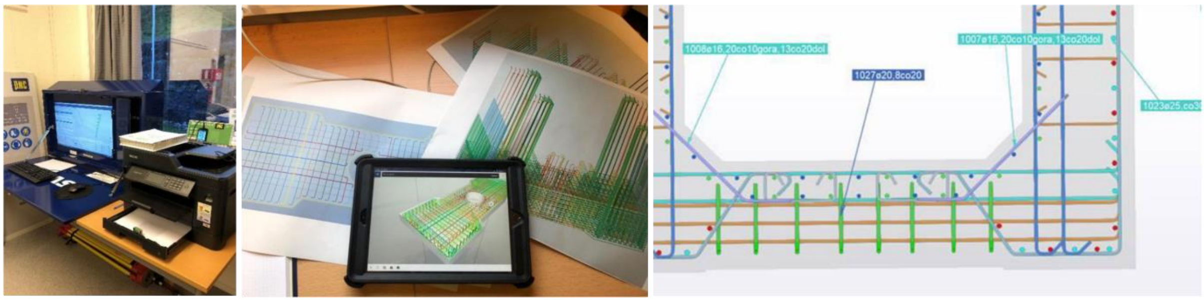

FIG. 1: Randselva bridge BIM use on the construction site (Ulvestad and Vieira, 2021).

The state-of-the-art BIM projects from the Nordic region described above highlight that BIM use on the construction site is not new but is often limited. These limitations include:

- Most state-of-the-art BIM projects are infrastructure projects and often specifically for reinforcement work. This may occur because software such as Tekla Structures is designed to support a 3D model-based approach for rebar and steel structures.
- It has been difficult to filter and measure objects in software such as Solibri and Navisworks, which do not function effectively for measuring on-site.
- Site workers lack the competencies to use software designed for expert users and there is usually a lack of resources on-site.
- Software and hardware limitations force workers to print POVs on paper rather than view BIM on mobile devices, which is comparable to working with static information sources.
- Standard contracts need to be modified to support BIM as the legally binding construction document.

In this paper we address these limitations by highlighting how BIM was used on-site in four Total BIM building projects. In these projects site workers interact with modern BIM-viewer software (i.e., StreamBIM) on mobile-devices, where BIM is the dynamic single source of information.

3. METHOD

This research examines four real-world case studies of building projects from the Nordic region. The first is a case study of Celsius, a new construction of an office and laboratory building in Sweden completed in 2020. The second in an ongoing new hospital project from Norway called Glasblokkene, stage 2. The two last projects are office building renovation projects in Sweden called Lumi and SB47. All the projects in the study used StreamBIM as the BIM-viewer software on the construction site.

The case studies are based on qualitative data gathered from interviews, site visits and workshops. Nine semi-structured interviews were conducted connected to the Celsius case lasting approximately 12 hours. We interviewed key actors from the Celsius projected that implemented the Total BIM concept including the VDC strategist; VDC on-site engineer and the project leader. Site visits to 4 projects and 4 workshops were conducted with industry digitalization experts (22 people) from Norway and Sweden. During these, further data were gathered from observations and discussions connected to the processes of implementing the future of on-site BIM. The interviews and site visits were filmed and recorded.

During the analysis of the qualitative data a holistic framework was used consisting of the thematic categories, ecosystem, technology, strategy and innovation, and organizing (Bosch et al., 2016; Disney et al., 2022a). In this paper we focus on two main themes, technology and organizing. The subthemes of technology were the technological components of BIM, interoperability (type of software), technological platform and framework for collaboration, and object information. The subthemes of organizing were processes, ways of working with BIM and cooperation with BIM between stakeholders.

In the latter part of this study, after analyzing the cases, a follow up seminar was held with the VDC strategist and VDC on-site engineer from the Swedish projects. We presented the themes of this paper to generate a discussion about concrete examples from their ongoing projects (Lumi and SB47).

4. FINDINGS AND DISCUSSION

The Total BIM approach sets new requirements on software and its user-interface as information is delivered on-demand. Users extract dynamic construction information on-site such as measurements, views and data that they need to perform their work. All information is accessible from the cloud when and where they need it. In the section below some of the key findings from the Total BIM approach are presented and discussed which address the commonly found issues in previous state-of-the-art BIM projects, mentioned earlier in this paper.

4.1 Dynamic views, sections and measurements

In modern BIM-viewer software (i.e., StreamBIM), POVs and measurements no longer need to be pre-defined. In all four of the case study projects, users on-site interacted with BIM on mobile devices to navigate in either 2D or 3D to their current work area. Once they were positioned in the correct location, they made fine adjustments using a touch screen interface to create the section or view that was most suitable. Site-workers used simple and intuitive measuring tools to add multiple measurements in the same view. The measuring tools automatically snap to objects that are possible to extend, which allowed for quick and accurate measurements between objects or gridlines (see FIG. 2 and FIG. 3). Measuring tools also exist that enable users to measure between multiple objects at the same time. Objects can be highlighted, hidden or filtered so that only relevant information is shown.

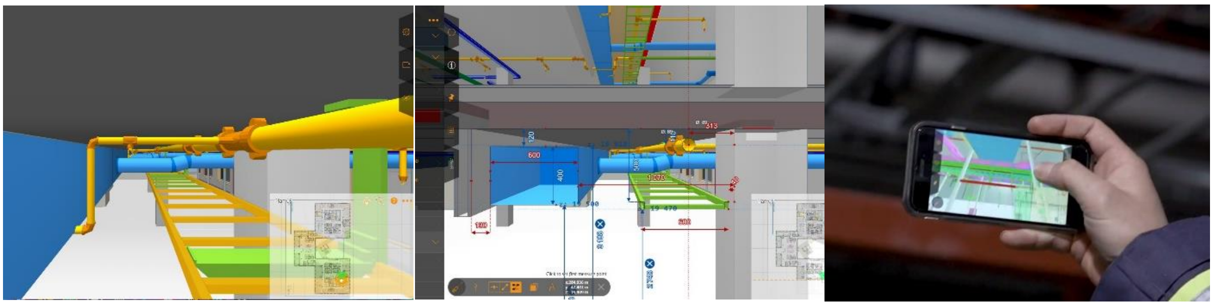

FIG. 2: Site-workers can use mobile devices to navigate in either 2D or 3D to their current work area and create unlimited sections and measurements in the same view (Image from case projects: Lumi and Celsius).

In the Total BIM project Celsius, they recognized the importance of creating additional measurement reference points that the construction workers could use later during construction. Construction surveyors used BIM as a source to replicate structure gridlines and valid referenced BIM-objects with physical painted reference points and lines on-site (see FIG. 3). In this context, the construction site can be recognized as dynamic as the construction develops towards the final product (i.e., building). Construction workers must adapt to the current situation on-site as different construction disciplines work in series and parallel. The design team delivers the design of the final product, but on the construction site the current state of the product is dependent on who has worked and what has been constructed on-site. Construction workers need to adapt to the current situation and find known reference objects or points to measure from and to, as seen in FIG. 3.Therefore, it was important to identify and to find valid referenced BIM objects and use structure gridlines for measuring references during construction.

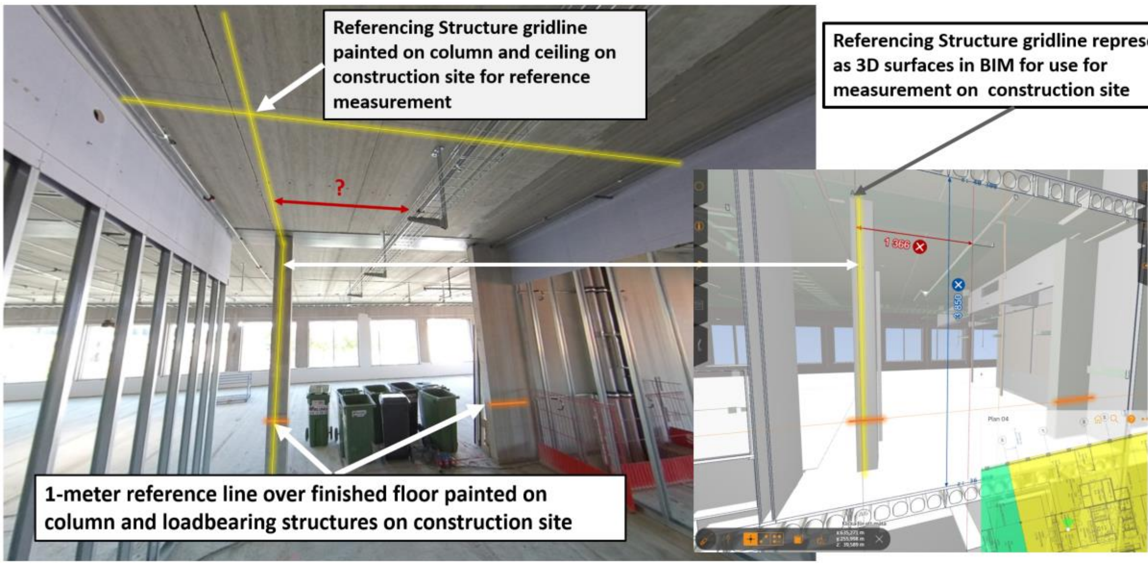

FIG. 3: BIM structure gridlines as measuring references on-site (Image from case project: Celsius).

Furthermore, a key feature of a Total BIM project is that workers can dynamically interact with BIM-viewer software to be able to create their own views and measurements related to the current situation on-site (see FIG. 2 and FIG. 3). They are no longer limited by static digital, or paper based "drawings" that have been created by design teams. Instead, site-workers dynamically navigate the model on location to gain a better understanding of the space they are working in without needing to switch to another drawing or document. Additionally, by using integrated BCF (BIM collaboration format) files designers are still able to provide the pre-defined views and measurements (i.e., POVs) if they are required to do so.

Previous state-of-the-art BIM projects described in this study show a situation where despite developing high-quality BIMs for production, use on-site as a dynamic source of information has been limited (Aune, 2018; Budarina, 2017; Cousins, 2017; Mershbock and Nordahl-Rolfsen, 2016; Rybus, 2022; Ulvestad and Vieira, 2021). In these projects, the hardware and software available was not functional or optimized for site workers to dynamically interact with BIM and take measurements on-site (Aune, 2018; Budarina, 2017; Johansson and Roupé; Rybus, 2022; Ulvestad and Vieira, 2021). Instead, what often occurred was that static images were created from BIM, measurements were manually added and then they were printed on paper. The information on these printouts was static, which is comparable with traditional ways of working where 2D drawings with measurements are produced by design teams. The parallel processes of creating high-quality BIM and printouts repeat many of the commonly found issues that existed previously in traditional projects, where the information is no longer dynamic, drawings may become outdated and are difficult to maintain (Davies and Harty 2013). In traditional projects, despite the problems maintaining static information sources, BIM is not trusted as it is not consistently updated (Påsse et al., 2022). However, in a Total BIM project all stakeholders focus on BIM as the dynamic single source of information. Recent advances in hardware and software have led to simple to use software on-site. The intuitive and easy to use features of this software on mobile touch screen devices has made it possible to work digitally with Total BIM in all project stages. Site workers can be quickly trained to use the software so that a dynamic work environment can be maintained, and users do not fall back on traditional methods. These modern BIM-viewer applications are still in their infancy and new features are being quickly developed. They have also developed significantly between Celsius (2018-2020) and the ongoing projects in this study. A concern might be that in the future as more features are added, that these too become expert packages where only advanced users can perform even simple tasks. To not lose the benefits of a simple to use package it is suggested that simple and advanced software modes are considered so that new users can quickly engage with the concept, which may help address the current lack of BIM competencies on-site.

Total BIM presents a new approach to construction where there is a single source of information throughout all project phases (from design to construction to facility management). New processes are created where users dynamically interact with BIM from the cloud. Users can be certain that the information they are working with is always up to date as it is automatically synchronized from the cloud. Changes can be made dynamically and communicated within the same application as the users are already working from. By using new hardware and software, BIM can be used effectively on-site for site workers to create the construction information they need to perform their work. The previous issues of measuring directly from BIM (Aune, 2018; Budarina, 2017; Cousins, 2017; Mershbock and Nordahl-Rolfsen, 2016; Rybus, 2022; Ulvestad and Vieira, 2021) are superseded by the improved functionality and optimization of new software packages. The four case studies show that site workers were now able to choose the views, sections and points of reference that they found most appropriate. Within these views, users can add measurements, dimensions and extract information to dynamically display what they needed to perform their work. Structure gridlines were replicated from BIM on the construction site to create additional reference points and enable construction to occur more accurately than what has previously been possible (FIG. 3). The new possibilities for site workers to be the creators of information on the construction site leads to many benefits. Designers traditionally create the section drawings that they decide are most appropriate. In a situation where they are paid per drawing rather than producing production-oriented BIM it could be argued that they may have sometimes chosen sections that were easy to represent. Instead, in a dynamic BIM environment site workers can produce the sections they want and need, so BIM becomes a digital virtual copy of what they are building, rather than a static document they are building from. They may also be able to plan their work better by exploring the model in advance. In the Norwegian hospital project, a plumbing subcontractor even chose to develop the BIM they received to a higher level of detail, i.e., production and manufacturing model, ensuring that when they arrived on-site, they could just focus on assembly. By constructing directly from the BIM-viewer software it is possible to instantly switch between 3D and 2D views to use the most appropriate medium for the task, which can help ensure more accurate construction.

Working with a dynamic BIM environment sets new demands on project stakeholders. Designers are tasked with developing BIM to a high level and no longer produce 2D drawings. In the Swedish office and laboratory case, Celsius, design costs increased by 18% compared with a similar traditional project (Disney et al., 2022a). Site workers become the creators of information on-site as they extract information from BIM. Management teams must also oversee the new digital processes and monitor communication through the software. At present in Sweden there are still challenges in some cases with allowed tolerances of 25mm during construction. One of the benefits with working from BIM is that exact measurements can be taken. By using custom reference planes and replicating structure gridlines on-site to create known reference points (the Swedish projects) workers never have to measure to objects further away than the length of a carpenter's ruler (the Norwegian project). However, standard regulations still allow tolerances during design that are suited to non-digital traditional work methods where 2D paper drawings were measured and scaled. This presents challenges during design and construction that must be managed today and, in the future, addressed by regulators, which may lead to greater levels of accuracy in the final built object.

4.2 Filtering

There are many ways to display and filter information in BIM-viewer software, (i.e., StreamBIM). Object information can be pre-sorted by design and construction teams into a simple tab that displays only relevant information for construction rather than the typical overwhelming amount of information usually associated with a BIM object. In the Swedish case study projects, custom tailored property sets on objects were created for site workers to gain easy access to information. This information was displayed under a tab simply called "PRESS here". The property sets contained the information that the site workers needed to perform their work, which was decided during discussions between BIM managers and site workers. The custom property sets also contained links to WEB-databases and PDF datasheets on objects for use during both construction and facility management (see FIG. 4A).

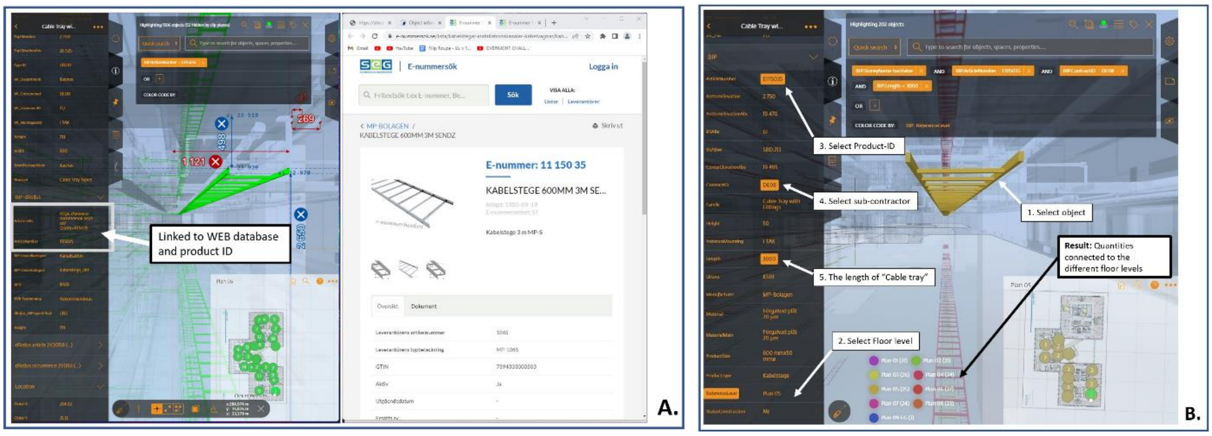

FIG. 4: (FIG. 4A): In the BIM-viewer (i.e., StreamBIM), BIM-objects had custom property sets that contained information such as product ID, WEB-database links and PDF datasheets, enabling a single source of information both during construction and facility management. (FIG. 4B): By clicking on a BIM-object and then different object properties an information filter automatically builds up a query of filters (Image from case project: Lumi).

Within these applications (e.g., StreamBIM) any user can view all the "layers" of BIM. Site workers were therefore able to view the whole model and gain a deeper understanding of how their work is meant to occur. If they wish to only see their part of the model, such as sprinkler systems, they can toggle all other "layers" to hidden. It was also possible to highlight a system, whilst making all others partially transparent to maintain an overall view (FIG. 4). Furthermore, it was possible to filter all objects of a certain type from which any object property or multiple properties can be chosen. Multiple properties can be selected by clicking on different object properties which automatically builds up a query to filter the information (see FIG. 4B). For example, in FIG. 4B, information can be filtered to create a quantity take-off for different floor levels using floor level, product ID, subcontractor and length of the product.

Filtering features in modern BIM-viewer software enable new levels of interactivity with BIM. Filtering has existed in software previously but has not been as intuitive or accessible as it is now. In combination with the navigation and measuring tools, users dynamically interact with BIM to gain a more thorough understanding of the space in which they are working. The tools also enable them to gain insight into how BIM objects interact with each other, and the current situation on-site as different construction disciplines work in series and parallel.

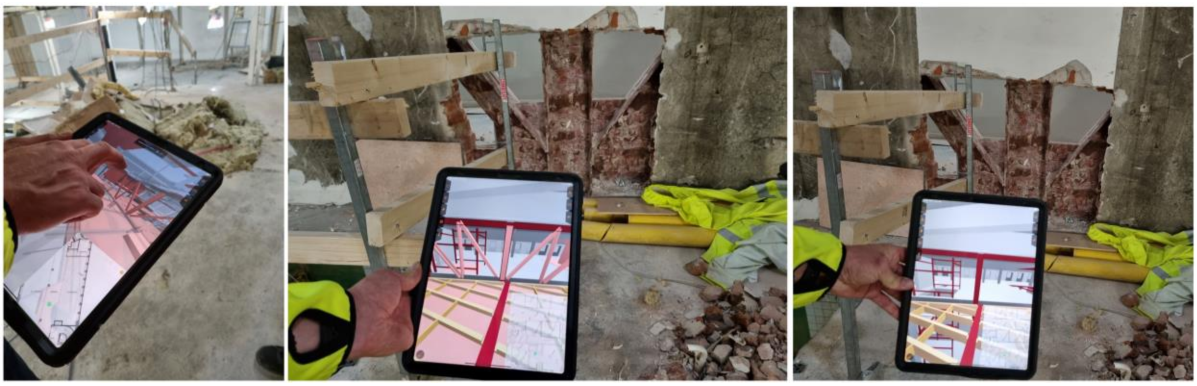

FIG. 5: Filtering BIM objects during a renovation project to understand which should be demolished and which should be kept (Case project: SB47).

In the Norwegian hospital project and the ongoing Swedish renovation projects, checklists were linked to an object's status to monitor each object's progress on-site. This information can be filtered in BIM to highlight the overall construction progress, or that of systems and zones on-site. It can also be used in a similar way when design and construction are occurring in parallel to understand which parts of the project have been developed to a significant extent for construction to begin, or to understand which objects to keep and which to demolish during renovation projects (see FIG. 5).

As BIM becomes more complex and objects have increasing amounts of data it is not surprising that novice users may find the information overwhelming. Therefore, powerful filtering tools are vital (FIG. 4 and FIG. 5). In the Swedish projects after discussions with subcontractors, important data attributes were sorted into a single property set that could be accessed with one simple tap on the screen. In this case production and assembly information such as subcontractor, assembly height above the floor, product ID, area, height and width etc. were recognized as important information. Within this property set links to WEB-databases and product data sheets were also later included, that eased navigation compared with static methods (see FIG. 4A). In the BIM-viewer software there was also an easy user interface to filter objects by their properties, displaying only those objects that matched the query criteria (see FIG. 4B). This is not possible to do in static drawings, where a lot of time might be lost to manually measuring or quantifying objects. Instead, the dynamic BIM environment makes it possible for the user to filter information and the view according to their needs. For example, this might be used in quantity takeoffs, logistics planning, or in renovation projects, which parts should be demolished, and which should be kept. When compared to traditional methods these processes are much easier and faster in a dynamic environment. Furthermore, the simple options to hide, show and highlight layers or objects in modern BIM applications make it easier for subcontractors to understand the space they are working in, which can lead to fewer errors and changes on-site.

4.3 Communication platform

Issues, discussions and notes can all be captured and communicated within the modern BIM-viewer applications (FIG. 6). These are not new ideas and already exist in construction software applications. However, the difference is in how they are implemented. Modern BIM-viewer applications are designed for use on mobile devices, on the construction site. Site-workers interact with both the hardware and software at the location they are performing their work. The integration between hardware and software facilitates easy capturing of images by using a devices in-built camera. If issues arise on the construction-site new topics can be created within the application. These topics can share information such as location (both in 2D and BIM), messages and photos from on-site (see FIG. 6). User rights to topics can also be assigned in advance so that issues can be quickly resolved. Communication occurs between site workers, design teams, managers and the different disciplines on-site. Site-workers receive responses directly through push notifications and within the application, which reduces handling times. By working dynamically with BIM on mobile devices rather than static information sources the communication processes become more integrated, since there is a single source of information. The different construction disciplines which work in series and parallel on-site, can communicate digitally with each other and show the current state on the construction site. This gives the next construction discipline on-site, understanding of the current state and can therefore plan and conduct work preparation before they arrive at the construction location. By combining the above-mentioned dynamic BIM-viewer application tools such as views, sections, measuring, and filtering with users taking photos of the current state on the construction site, the BIM-viewer becomes a single source of information. This was evident in the construction project of the new office and laboratory building in Sweden i.e., Celsius (see FIG. 6) (Disney et al., 2022a).

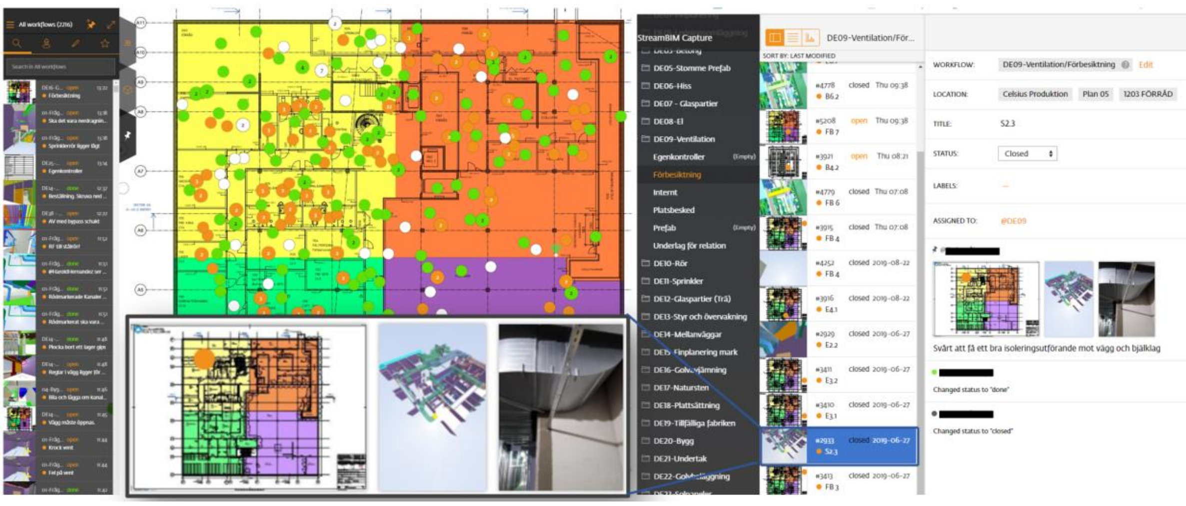

FIG. 6: During the projects StreamBIM was used as a communication platform where requests for information (RFIs) were created and answered. Users received push notifications on their mobile devices when their RFI got an updated massage or status (Image from case project: Celsius).

In the Celsius project StreamBIM was primarily chosen to be used for construction workers to retrieve information, but it unexpectedly became a platform for communication (FIG. 6). The project was rated highly in worker surveys for communication (Disney et al., 2022b). Initially management teams thought that they had communicated the same way as in previous projects. They later realized that having a single source of information (BIM-viewer software) connected commonly unconnected information sources and enabled communication to occur openly, rather than for example behind closed e-mail chains or phone calls (Disney et al., 2022b). The BIM-viewer became a communication platform for issue reports, checklists, inspection documentation, RFIs and as-built documentation. It also enabled communication to occur more easily between design and construction teams, as well as between the different disciplines on-site. Communicating digitally on-site is not new, but by integrating features such as photos, 2D and 3D views, location, descriptions and assigned roles with the dynamic BIM use on-site, it was simply easier and quicker to communicate issues. Issues that arose on-site were monitored by site management using data visualization software (Norwegian hospital and Swedish renovation projects) that quickly alerted them to the most urgent issues. Once resolved site workers were notified with mobile push notifications, on the devices which they were already working from. Integrating and digitalizing communication into the same platform as the construction documentation, created a single source of information and supported the Total BIM concept. Combining these information sources created a more transparent and streamlined process rather than attempting to maintain traditionally found unconnected static information sources.

4.4 Checklists, object states and scheduling

All four of the case study projects used checklists and controls within StreamBIM. Like the communication tools described above, the idea of checklists and controls are not new. However, what are commonly found as static or unconnected information sources can instead be found integrated with the other interactive tools in one application, creating a dynamic work environment. In the SB47 project objects in BIM had checklists connected to status and different sub-activities conducted by different subcontractors (see FIG. 7).

FIG. 7: Checklist for different sub-activities for door assembly (Image from case project: SB47).

As site work was performed on the object, workers updated the object's status. By assigning objects to individuals, subcontractors or project teams, progress could be monitored remotely by management teams. Checklists can also be linked to scheduling tools that are available within BIM-viewer applications to make any necessary adjustments. These checklists can be used to visually highlight construction teams that may be behind schedule. Information from StreamBIM in these projects was also exported to tailored data visualization software such as Power BI, which provided management teams with new analysis opportunities. In addition to tracking object states, the projects in this study have used these features for quality controls, safety checks and requests for information.

The Total BIM concept and this new way of working, set new demands on the process of the systematic quality assurance of BIM and its information. BIM is the legally and contractually binding construction document for designers, management and subcontractors and it becomes the single source of information. However, on its own this is probably not enough. To ensure the right quality levels are achieved when it comes to constructability, e.g., how well things "fit together on-site", simply being legally binding is insufficient. Knowledge from site workers must be considered and a quality assurance process must be created. In the Norwegian hospital project, they recognized this and implemented a 20 week, 7 step process. This created a structured approach to ensuring milestones were achieved in a timely manner and the maturity of BIM was developed in time to required levels of development (LOD) or more specifically as used in the hospital project, model maturity index (MMI). During this 7 step process production teams were brought in to communicate with designers and provide site knowledge. These production teams were involved 17 weeks before construction and had a final chance to review the information 8 weeks before production, at which point BIM was developed to 400 MMI, a level that could be trusted on-site. This early involvement from subcontractors sets new requirements on them. The construction document is no longer a static document from which they work from, but they are part of a dynamic process in the producing BIM. Therefore, standard contracts may need to be reviewed to include these new roles. The early involvement ensures that site workers have access to the most suitable construction document from which work occurs on-site. Site workers are no longer the recipient of static 2D unconnected information sources, but they assist in the dynamic creation of information both during design and construction. By working this way, detailed and important production and assembly information could be integrated into BIM, which may create a more efficient construction site.

Another challenge is that design and construction often occur in parallel, complicating the process of setting statuses on objects. As mentioned above the Norwegian hospital project, used a 20 week, 7 step process where MMI status was added on BIM objects. However, in the Swedish office building projects, design changes occurred very late in the process as new rental tenants come into the project. This sets strict requirements on controlling design and change orders on the construction site. Decisions must be anchored and negotiated between the various actors before construction occurs. Any design changes are automatically sent to the cloud. While a benefit in some regards, the BIM-viewer automatically shows the most up to date version. This can be challenging and sets new demands on trust and management. At present it is possible to track these updates digitally but what often happens is that many objects change state and information overflows occur. Instead, the changes are manually tracked in static documents and then communicated to site workers and sub-contractors through change orders. These updates occur so frequently and dynamically that tracking them can be difficult and as a result it also places new demands on leadership and management. In a Total BIM project all information is linked to BIM. Controlling the status of objects in BIM is just in its infancy and there may be many future opportunities in terms of how this information is handled. At present this information is mostly used for controls and monitoring but perhaps in the future it can be more dynamic and used to feedback into other processes. For now, the main advantage of object controls in BIM over traditional methods is that the information is more integrated, and the other benefits can be leveraged to a greater extent.

By linking BIM objects to controls that correspond to the object's status, (see FIG. 6 and FIG. 7) management teams are provided with new opportunities for monitoring the construction site. In Total BIM, BIM becomes the virtual copy of the construction site, which could be a base for digital twins in the future. By linking wireless sensors to BIM objects, such as wireless moisture sensors of concrete, management teams could be provided with real-time data feeds for construction planning and monitoring the construction site. Furthermore, these concepts can be used to see which objects are ready for construction, complete or certain sub-activities fulfilled. A future goal for the Swedish construction management company is to automatically link progress to scheduling within the application but at present it is challenging to implement effectively.

5. CONCLUSIONS

Traditional construction projects are hindered by the parallel processes of delivering 2D drawings and BIM because 2D drawings are difficult to maintain and trust is lost in BIM as it ceases to be consistently updated (Davies and Harty, 2013; Påsse et al., 2022). Previous state-of-the-art BIM projects have also been limited by hardware and software where it was difficult to extract measurements directly from BIM on-site (Aune, 2018; Budarina, 2017; Cousins, 2017; Mershbock and Nordahl-Rolfsen, 2016; Rybus, 2022; Ulvestad and Vieira, 2021). Therefore, until recently construction has mostly occurred from static unconnected information sources. However, the Total BIM concept applies a new dynamic way of working, where there is a single source of connected information. The Total BIM on-site processes from the four case studies are not new ideas. What is new and shown in this study is the way that these processes are dynamically implemented, which changes how on-site construction occurs.

A key aspect of Total BIM is that site workers can dynamically extract and create construction information on-site. Previous attempts have been made to achieve this but have been limited by software tailored for expert users, difficulty adding information to objects such as measurements and lack of trust in BIM (Aune, 2018; Budarina, 2017; Cousins, 2017; Mershbock and Nordahl-Rolfsen, 2016; Påsse et al., 2022; Rybus, 2022; Ulvestad and Vieira, 2021). The four projects in this study have shown that with modern BIM-viewer software it is possible for construction workers to dynamically filter, create and extract information from BIM. Simple to use measuring features, pre-filtered property sets, and query filtering tools enable users to work in a dynamic BIM environment rather than with static information sources. On-site users create the most suitable information they need for their tasks. However, due to the new work methods, new demands are set on project stakeholders and challenges remain regarding allowed tolerances, which may need to be addressed by regulators.

Although it was initially unexpected the BIM-viewer application became much more than a tool for interacting with BIM. In all four projects it became a communication and management platform, where commonly found unconnected information sources were integrated. By using mobile devices, photos from on-site were linked with information from BIM and short descriptions to accurately document issues, which reducing handling times. Management teams were also able to better observe the status on-site as all the information was connected.

Total BIM sets new demands on the process of the systematic quality assurance on BIM and its information since BIM is the legally and contractually binding document for all stakeholders. A structured approach was implemented where site workers were involved during the design stage to assure constructability and an accurate BIM. This changes the role of site workers from recipients of static information sources to assisting in the creation of dynamic information, both during design and construction.

This research addresses and answers the question, "how could BIM be used throughout a construction project as the dynamic single source of information on the construction site, i.e., Total BIM?" Until now the main challenges have been implementing BIM effectively on-site. The case studies show that static 2D "drawings" are no longer necessary for the construction site and it is possible to use BIM throughout all project phases as a dynamic single source of information. Total BIM may even be the preferred method of the future and save money (Disney et al., 2022a; Rybus, 2022; Ulvestad and Vieira, 2021). This research highlights key dynamic processes that are required to implement the Total BIM concept on-site and these findings can be used to support on-site implementation and strategy work of Total BIM. They also contribute practical concrete examples where there is a lack of empirical studies about on-site BIM implementation.

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