AUGMENTING BIM WORKFLOWS IN CONSTRUCTION PROJECTS

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Abstract. Augmented Reality is expected to play a critical role in maximising the potential of BIM on worksites in the construction stage. However, few studies have focused on BIM-based AR use cases, and the change from existing BIM practices to more integrated models. Using observations from BIM and BIM-AR implementation in real project settings, we propose a workflow for BIM-AR use cases to support the installation and validation of MEP services. Through the proposed workflow, we highlight how the use of BIM-AR on worksites can improve the design feedback loop and hence create a collaborative learning environment and improve future designs.

1. Introduction

Ensuring that the design of a building meets the functional, aesthetic, and economic requirements is a crucial and demanding task that involves coordinating various aspects of the design. In particular, mechanical, electrical, and plumbing (MEP) services, including medical systems, are considered the most complicated components in a building. The design coordination of MEP services has proved to be challenging compared to other trades (Teo et al., 2022). Building Information Modelling (BIM) is a recent advancement in the built environment that has improved design coordination and collaborative practices (Amin and Abanda, 2019). Despite the established advantages of BIM, project participants continue to encounter substantial obstacles that undermine the design coordination process, even when BIM tools are easily accessible (Alsuhaibani et al., 2022). Around one-third of design coordination issues remain undetected and are discovered during installation (Mehrbod et al., 2019). Many of the issues discovered onsite go beyond physical conflicts to include issues related to constructability and operability (Alsuhaibani et al., 2022). Construction knowledge such as constructability and material management is closely related to the design input, and so, the capture of such knowledge is a critical element in improving the design quality of future buildings (Henderson et al., 2013). There is a lack of feedback on design during construction as issues are solved as they arise in isolation from the design input (Göçer et al., 2015, Chen and Xue, 2020). With the accumulation of issues resolved on the spot, discrepancies increase between as-designed and as-built, making the new MEP layouts not suitable for installation (Wang et al., 2016). This adds more workload on the as-built modelling process which is considered time-consuming and resource-intensive. Subsequently, the resulting as-built model does not represent an accurate and complete representation of building components that can be developed as a facilities management (FM) model (Ensafi et al., 2021). And so, the existing BIM workflow of design coordination and as-built modelling suffers a bottleneck in the information flow between the office and the site. Many studies have considered the reliance on printed 2D drawings for the exchange of technical information as one of the main reasons for this bottleneck (Mehrbod et al., 2019, Nassereddine et al., 2020). The reliance on printed drawings seems inevitable by site professionals as they do not have access to BIM tools on worksites where screens are limited (Wang et al., 2016).

Augmented Reality (AR) is a recent advancement in visualisation technology that has the potential to improve onsite productivity in construction projects (Sidani et al., 2021). The benefits of integrating AR with BIM are mainly attributed to improving information flow and collaboration between the office and worksite (Wang and Chen, 2020, Alsafouri and Ayer, 2019). Using BIM-based AR, site professionals can visualise and interact with full-scale 3D BIM, and collaborate with the office using the superimposed model. The majority of studies investigate general AR applications such as training, hazard recognition, and assembly guidance which do not depend on interacting with full-scale BIM models (Amin et al., 2023). This has diluted the focus needed on BIM-AR considering the fundamental differences between BIM-AR and general-purpose AR applications. Differences include the need for a meticulously designed software architecture to effectively transfer the large amount of information in design models to worksites using BIM-AR. In addition, advanced localisation techniques are needed to attain the precision and stability of superimposed models (Amin et al., 2023). Furthermore, the majority of BIM-AR research is more focused on the developer perspective than the practitioner perspective. Although a large number of studies have highlighted the technical and technological challenges of general AR applications, fewer studies have contextualised their findings in real-world examples or explored insights from practitioners (Nassereddine et al., 2022a, Amin et al., 2023). Many scholars have argued the need to align the tools of BIM-AR with the specific requirements of existing practices in the construction industry (Davila Delgado et al., 2020a, Xu and Moreu, 2021). To that end, this article identifies use cases for BIM-AR through the lens of a practitioner and proposes changes to existing BIM workflow to leverage BIM-AR in light of the identified use cases.

BIM requires business transformation with regard to mindset, process, and platform (Amin and Abanda, 2019). BIM-AR is much the same, requiring closer academia and industry collaboration to advance the technology. In this article, we reflect on personal experience and observations of implementing BIM-AR in real project settings in the pre-construction and construction stages. A modified BIM workflow that incorporates the use of AR in its phases is proposed. First, through a literature review, we survey the use cases of AR identified in prior studies and extract the use cases that can be relevant to BIM in the context of onsite installation and validation activities of MEP services. Second, existing BIM workflow is described to highlight the bottlenecks in information flow between the office and the site. Finally, a new workflow for BIM-AR is proposed in the context of the identified use cases. At this point, we investigate how the use of BIM-AR in worksites can benefit the design feedback loop and create a collaborative learning environment to improve future designs.

2. Literature review

Extended Reality (XR) is the term used to describe different immersive visualisation technologies. VR and AR are the two major subsets of XR. VR creates a virtual environment that replaces the real one, while AR augments the visual field with digital information (Milgram and Kishino, 1994). Because the main purpose of AR is to display digital information in the context of the surrounding physical environment, it is more useful for use in field settings, i.e., in the construction and operation stages. On the other hand, VR is more useful for training and visualisation tasks in the design stage. Several researchers attempted to investigate AR use cases and categorised them based on different criteria. Table 1 shows a summary of the most relevant studies that have surveyed the use cases of AR in the built environment. Despite the potential of the integration of BIM and AR to support construction activities onsite, few studies have focused on BIM-AR use cases as the main topic of research. The majority of research on AR usually investigates general-purpose AR applications that do not depend on using BIM models. This has diluted the research output on BIM-AR in the construction stage. In addition, there is a lack of practitioner perspective in the classification criteria of the identified use cases.

Table 1 Summary of the most relevant studies that have surveyed AR use cases in the built environment

Article	Stage	Technology	BIM-AR focused?	Conclusion of Research
(Schiavi et al., 2022)	Design to Operation	AR/VR	No	Identified two categories for AR and VR use cases: activities and training
(Nassereddine et al., 2022a)	Pre-Construction to Operation	AR	No	Identified 42 use cases for AR. The use cases are grouped under three clusters that are ranked based on their usage potential
(Nassereddine et al., 2022b)	Pre-Construction to Operation	AR	No	Identified 23 use cases and mapped them to the desired capabilities of AR systems.
(Davila Delgado et al., 2020b)	Construction	AR/VR	No	Identified six categories: stakeholder engagement, design support, design review, construction support, operations and maintenance support, and training
(Chen and Xue, 2020)	Design to Operation	AR	No	Use cases are grouped per stage, three are identified in the design stage, seven in construction, and six in operation

Through the lens of a practitioner in MEP design and construction, the installation of the services is the key activity in the workflow. The BIM process prior to installation aims to deliver a fully coordinated design that considers all aspects related to constructability, maintainability, and performance. After installation, the BIM process aims to accurately capture the changes made during installation to develop as-built models. Based on this perspective, we propose a classification for BIM-AR use cases based on the activities conducted before and after the installation of the MEP services. The proposed classification acknowledges the potential of BIM-AR to relieve the bottleneck in the information flow to and from the construction site by enabling access to building information through AR onsite. Table 2 shows the proposed BIM-AR use case classification based on the findings of Nassereddine et al. (2022a), Nassereddine et al. (2022b), and Chen and Xue (2020). The effective implementation of these use cases requires a change in everyday BIM practices. In the next section, we reflect on existing BIM workflows and highlight the information flow bottlenecks that can be relieved using BIM-AR.

Table 2: BIM-AR use cases for MEP installation

Category	Description	Use cases
Pre-installation	Constructability and construction planning	Layout visualisation, clash detection (digital-digital and digital-physical), site logistics, equipment delivery route, design alternatives, remote collaboration, augmented mock-ups, pre-site modular component factory inspection, 4D model visualisation
Post-installation	Inspection and progress management	Remote inspection, 3D scanning, client quality management, 4D model visualisation, progress tracking, as-built vs. as-designed validation, as-built model development, workshop prefab component inspection

3. Reflecting on existing BIM workflow

The existing BIM workflow can be divided into three phases. The first phase includes conducting 3D model-based cross-trade coordination through consequent quality gates. This process involves several cycles of clash detection and model renditions between project participants. Despite the availability of many robust BIM collaboration tools, the design coordination process seldom results in a constructible model with the desired quality. This can be attributed to factors like conducting design coordination in silos, last-minute changes, and focusing on producing a clash-free model overlooking aspects related to constructability, maintainability, and operability. The resulting model is then used to produce 2D drawings that reflect the coordinated design. In most cases, reviewing 2D drawings may require model-based changes and require more revision cycles. The practice of using printed drawings for information exchange has been the norm for decades and will probably be used for years to come. This form of media is more accessible and can be easily shared between stakeholders. However, generating 2D drawings from 3D models is a challenging, resource-intensive, and time-consuming process. In addition, 2D drawings do not have the capacity to communicate all the necessary design information, leading to misinterpretations and rework onsite (Wang et al., 2014). At this point in the BIM workflow, a bottleneck is created in the flow of information by communicating 3D design information to the worksite using 2D printed drawings.

The second phase involves interpreting design information from printed drawings and installing the services. As more services are installed, misinterpreting printed drawings, the limited access to BIM, and the difficulty in communicating with the office may lead the specialists and subcontractors to make on-spot changes to the design. The identification and fixing of errors onsite is usually a reactive process as they are discovered during installation on a case-by-case basis. And so, the discrepancies between as-designed and as-built increase, adding more workload to the as-built modelling process. Ensuring there is consistency between as-designed and as-built is important to ensure that a design is workable onsite – but also that there is an effective and documented record of what has been built, so as to learn lessons and use the most optimal design for future projects.

The third phase involves capturing built elements to develop the as-built model. The reality capture process is usually carried out using one of two or both methods: laser scanning and redline markup drawings. Although laser scanning can provide more accurate results than other reality capture technologies, the processing may be impeded by external noise and can be easily obstructed by an intricate network of services. In addition, the generated point cloud models are usually of a large size which can impact the performance of mainstream BIM authoring tools. On the other hand, redline markups do not usually convey what changes have been made and make it challenging to develop the as-built models. In many cases, the amount of information is insufficient and necessitates making extra work by taking additional photos and site visits which extends the time taken to develop the as-built model. The resulting as-built model is usually inaccurate and does not satisfy the requirements needed to be used in the FM stage. Figure 1 summarises the existing BIM workflow and highlights the bottlenecks in information flow between the different phases. The next section proposes a BIM-AR workflow that relieves the information flow bottlenecks by visualising and interacting with full-scale models onsite and facilitating collaboration between the site and the office.

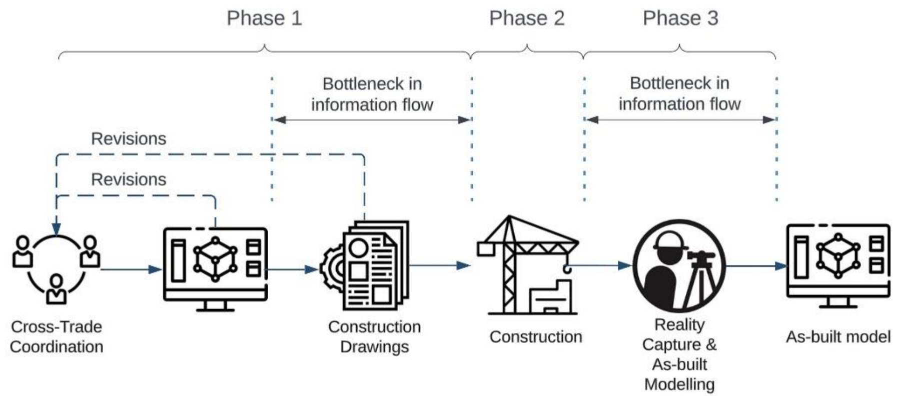

Figure 1 summary of the three phases of describing existing BIM workflow and the locations of the information flow bottlenecks

4. Proposing a new BIM-AR workflow

The core objective of BIM is to shift the peak of generated information in earlier stages in a project lifecycle (MacLeamy, 2004). Similarly, BIM-AR aims to create early feedback on MEP design before onsite installation, in other words, doing more work planning the installation of the services to guarantee a streamlined construction process. BIM-AR can transform the reactive approach of discovering and resolving issues as they arise into a proactive approach that involves the early discovery of issues before services installation starts. The BIM-AR workflow proposes three phases (Figure 2). In the first phase, BIM-AR systems are used to superimpose interactive models onsite and enable different modes of collaboration with the office. Design rehearsals can be carried out and streamed to enable remote inspection. Operation and maintenance practitioners and professionals from non-engineering domains can attend rehearsal sessions to visualise design information and provide their feedback. This feedback can be stored centrally in the BIM model in the form of markups, text, or video to create a design-construction feedback loop and hence improve future designs. We use the term "augmented design" to refer to the design-construction learning created by BIM-AR (Figure 2). The second phase involves installing with visual confidence of design reliability and compliance with standards. The third phase, capture, involves capturing the elements that have just been installed using the same BIM-AR system. Similarly, BIM-AR seeks to shift. The following subsections describe the proposed workflow in the context of the identified BIM-AR use cases in Table 2.

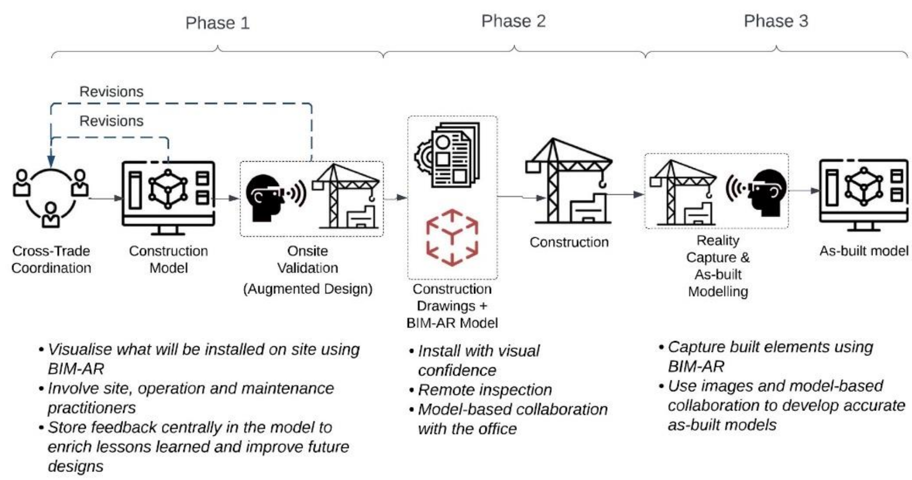

Figure 2 a proposition for a new BIM-AR workflow to improve the flow of information between the office and the site

4.1 Pre-installation augmented design

In pre-installation use cases, BIM-AR is an additional quality gate that takes place onsite to further validate design information before starting installation. The objective of BIM-AR then is to visualise full-scale design information in the context of the physical surroundings to update the design taking into consideration the deviations in built elements, including architectural and structural. The additional quality gate guarantees that aspects related to constructability, maintainability and operability are considered in the design. This enables a proactive practice of identifying and resolving issues before installation instead of discovering them in a case-by-case manner. Using BIM only to achieve this proved to be difficult as onsite practitioners don't have easy access to screens and can be less experienced in dealing with 3D models. The model-based collaboration between the site and office -enabled by AR- can significantly reduce the number of revision cycles and site delays. And so, because the production of 2D drawings from 3D models is time-consuming and resource-intensive, the optimum stage to use BIM-AR is during the BIM coordination and before the generation and submission of the printed drawings. Figure 4 and Figure 3 show two incidents of pre-installation BIM-AR use cases that involve clash detection and site logistics. In both incidents, the validation session was streamed live to allow remote inspection.

Figure 4: digital-physical clash detection. Pre-installation validation using BIM-AR shows 75mm misalignment between built ductwork openings and to-be-installed ducts. Image courtesy of XYZ Reality Limited. (XYZ Reality, 2022)

Figure 3: site logistics and equipment delivery use case. Pre-installation validation using BIM-AR shows the wrong orientation of the equipment compared to its orientation in the design model. Image courtesy of XYZ Reality Limited. (XYZ Reality, 2022)

Although the use of BIM has provided a centralised approach to generating and storing information, practitioners outside the design team had little access to BIM tools. Individuals who are not part of the design team usually do not have the BIM experience to navigate, understand, and comment on design 3D models using screens. Although BIM-AR tools may have a steep learning curve initially, users can become more familiar with the tools and their features faster than BIM tools (Meža et al., 2014). BIM tools usually require a significant amount of training and experience to fully understand their features and functionalities. BIM-AR creates a new medium for generating and sharing information on worksites for practitioners with construction, operation, and maintenance backgrounds. This medium creates an opportunity to easily provide real-time feedback on the design before and during installation, in what we call in this article "augmented design". The feedback on design can be stored in the form of images showing digital elements superimposed on physical elements, text, markups, voice notes or video. Figure 5 shows means of providing feedback on design using BIM-AR.

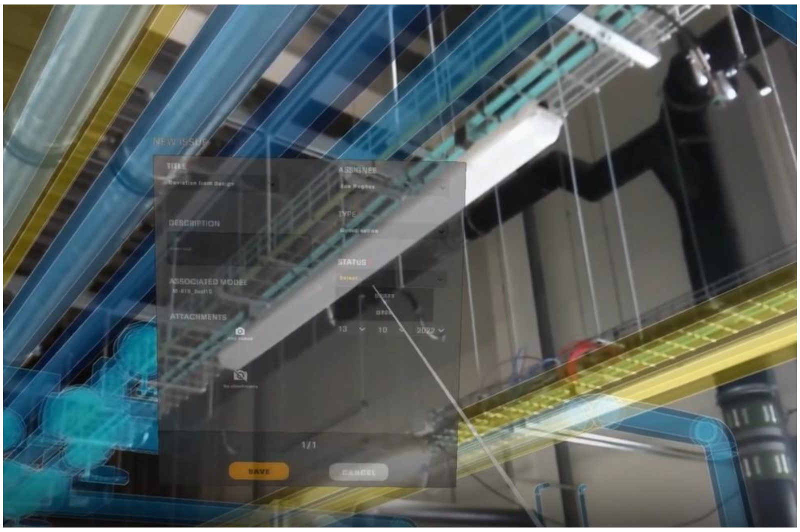

Figure 5 providing real-time feedback on design before and during installation.
Image courtesy of XYZ Reality Limited (XYZ Reality, 2022)

The integration with cloud-based document management systems has enabled generating and retrieving different forms of feedback that are linked to locations or elements in the design model. And so, through closer design-construction integration the speed of learning is real-time, and the digital audit trail is clearer.

4.2 Post-installation

The objective of post-installation use cases is to timely capture installed items in an accessible form that can be easily used to develop as-built models. If construction models are not updated promptly, the design coordination cannot be efficient because what is being coordinated does not reflect what is in the field. The early integration of BIM-AR in the construction stage can significantly reduce the workload in as-built modelling, by enabling the timely update of as-built models. The tedious workflow of comparing point cloud models to construction models can be reduced by simply taking images and footage of the built elements once they have been installed (Figure 6). With the advanced interaction and collaboration capabilities, superimposed elements can be updated onsite to reflect their progress status, enabling a timely update of progress.

Figure 6 post-installation progress tracking using BIM-AR. Location deviations between installed rainwater pipes and their corresponding elements in the construction model. Image courtesy of XYZ Reality Limited (XYZ Reality, 2022)

Overall, the early detection of errors and risk mitigation prior to starting installation can minimise rework and lead to cost savings. The shared visualisation platform enhances communication and decision-making among stakeholders, reducing change orders and costly revisions. In addition, the minimisation of laser scanning activities through the use of BIM-AR images can lead to both budget and schedule savings, and more accurate as-built models. And so, the use of BIM-AR in construction sites can have lifecycle benefits and a positive impact on project costs. However, there is limited robust evidence on the quantification of benefits of using BIM-AR. There is a need for independent evaluation through more real-world case studies to quantify the benefits and the potential return on investment.

5. Conclusion and recommendations

The design coordination of MEP services in construction projects proved to be a challenging and demanding task. The adoption of BIM improved collaborative design coordination practices, yet these improvements have remained exclusive to the design team. Project participants continue to encounter obstacles that have not been resolved in design during installing MEP services. The reliance on printed 2D drawings as the main information exchange method creates a bottleneck in the flow of information between the office and the site. The integration between BIM and AR has the potential to expand the scope of BIM beyond design to the construction stage by enabling practitioners to visualise and interact with full-scale design models on worksites.

Through a literature review, we have surveyed use cases of BIM-AR in the context of the activities related to the coordination and installation of MEP services. By reflecting on personal experience, observations have been made on existing BIM workflow, highlighting the points where bottlenecks in information flow are created. We propose a BIM-AR workflow that can compensate for the shortcomings of the existing BIM workflow. Using BIM-AR, practitioners with construction, operation, and maintenance backgrounds can identify design issues early before starting installation. Although the benefits of BIM-AR appear to be mainly in the construction stage, BIM-AR enables an augmented design experience by improving the design-construction feedback loop, and hence creates a collaborative learning environment and improves future designs.

Studies have already shown the practicality of BIM-AR, making it applicable to apply these results in actual project scenarios and engage more professionals in the process. To do so, it is necessary to conduct more research on the integration of three critical components: people, process, and platform. Together, these elements form the framework for successful BIM-AR implementation within the construction sector. People play a crucial role in driving the success of BIM-AR, as it requires a collaborative mindset and a willingness to embrace change. This involves training and upskilling as well as improving the perception of the technology in the industry. The process component involves establishing standardised workflows that govern the use of BIM-AR tools and technologies. In this paper, we have summarised BIM-AR use cases and proposed a workflow to deliver the objectives of these use cases. However, more research is needed on for example integrated BIM-AR workflow and data schemas (e.g., superimposed onsite to address users' models requirements) and platform benchmarks (e.g., an evaluation method that can cope with the rapid development of the technology).

6. Acknowledgement

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May 27, 2023

Subject: Revision and resubmission of manuscript: Submission 6541

Dear Conference Committee,

I am writing to submit a revised version of my conference paper titled Augmenting BIM workflows in construction projects’" for consideration for the upcoming 30th International Workshop on Intelligent Computing in Engineering. We appreciate the opportunity to revise and resubmit the paper based on the valuable feedback received from the reviewers. We have carefully addressed the reviewers' comments and suggestions either by modifying the manuscript or responding to the comments in this document. We value the insights and expertise of the conference committee and the reviewers, and we are confident that the revision has improved the contribution and originality of the research.

Sincerely,

Khalid Amin

The Bartlett School of Sustainable Construction
University College London

Comments from Reviewer 1:

Comment:
This abstract is promising and fitting. For the development of the full paper, I have the following suggestions:

Response:
Thank you.

Comment:
- Is your scope on the Design phase or rather on the Construction phase? That is quite relevant, as the purpose is different, and the way in which AR is then used, likely also becomes different. Who will be your user? The designer, the worker on construction site, the BIM modeller? If it is the BIM modeller, who mainly works in a virtual environment, then you will likely need a VR strategy rather than AR strategy.

Response:
Thank you for your comment. The scope is on the construction phase, and the users involve BIM and site professionals who are involved with the design coordination and installation of MEP services. We have furthered clarified the topic in the full article by discussing onsite use cases for BIM-based AR and providing images from construction sites in real-world projects.

Comment:
Please add specific cases with specific detail, so that your conclusion is not "early adoption may lead to improvements", but becomes something much more concrete and meaningful. A conclusion that "X may be useful" is a very poor conclusion. Please specify where and how something can be useful, and show why with a specific case.

Response:
Thank you for your comment. Details about the use cases including workflow description and diagrams have been added. The conclusion has been improved by including details about the specific benefits of using BIM-based AR for MEP services installation.

Comments from Reviewer 2:

Comment:
This article provides a detailed analysis of the existing Building Information Modelling (BIM) problems encountered in design coordination and construction processes. It proposes a new workflow based on BIM and Augmented Reality (AR) to improve existing BIM practices. The real-time visualization and interaction capabilities of BIM-AR at construction sites help solve issues in traditional BIM workflows, demonstrating innovation.

The article has a clear structure, with sections covering reflections on existing BIM workflows, the proposal of the new BIM-AR workflow, and specific applications and practice descriptions at different stages. The article is well-organized.

The content includes case analyses of actual applications. A detailed discussion of the application of the BIM-AR system before, during, and after construction is presented, showcasing the practical effects and potential value of this new workflow.

Response:
Thank you.

Areas for further exploration and improvement in the article include:

Comment:
A lack of detailed description of the integration of AR technology with existing BIM software. More specific explanations are needed for handling real-time data synchronization, positioning, and navigation, including design methods and tools.

Response:
Thank you for your comment. The article acknowledges the plethora of BIM-AR studies that have focused on the software developer perspective, and proposes the need to start looking at the technology through the lens of the actual users who will implement the technology. Hence, the focus of the article has been more on the BIM side of things in terms of process rather than AR techniques and software integration.

Comment:
The impact of the new model on project costs and investments needs further clarification. While improving project collaboration efficiency, emphasis should be placed on whether the new workflow has economic advantages, and whether the relationship between increased efficiency and project investment returns can be discussed.

Response:
Thank you for your comment. The following paragraph has been added at section 4.2:
"Overall, the early detection of errors and risk mitigation prior to starting installation can minimise rework and lead to cost savings. The shared visualisation platform enhances communication and decision-making among stakeholders, reducing change orders and costly revisions. In addition, the minimisation of laser scanning activities through the use of BIM-AR images can lead to both budget and schedule savings, and more accurate as-built models. And so, the use of BIM-AR in construction sites can have lifecycle benefits and a positive impact on project costs. However, there is limited robust evidence on the quantification of benefits of using BIM-AR. There is a need for independent evaluation through more real-world case studies to quantify the benefits and the potential return on investment".

Comment:
Question: The current application cases do not fully demonstrate the applicability of the new workflow. Do the authors plan to apply it to projects or is this research supported by such plans? Improve the resolution and text size of figures 1 and 2.

Response:
Thank you for your comment. The new workflow has been developed based on personal experience and observation of how BIM-based AR been used in real projects for both pre-installation and post-installation use cases. This has been done through a KTP project between UCL and XYZ Reality Limited, an AR developer. The text size in the figures has been increased and the resolution of the icons has been improved.