Research Article

Augmented Reality for Identifying Maintainability Concerns during Design

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In a building context, decisions made early in the design phase can have a major impact on maintainability of the resulting facility. Effectively leveraging the knowledge of facility management teams in the design stage can lead to improved maintainability in the operation phase, but this feedback can be challenging to elicit during the design stage because facility management teams may not be formed by the time of design. This requires designers, who may not have facility management experience, to think like facility managers in order to consider the needs of the maintenance teams. This paper examines the extent to which different visualization media may be able to enable individuals without prior maintenance experience to identify maintainability concerns in a design model. Student participants, without prior maintenance experience, were randomly assigned to explore a design to assess maintainability concerns with either augmented reality (AR) or a traditional computer screen for viewing a Building Information Model (BIM). Their perceptions, behaviors, and statements were recorded and analyzed. Results indicate that BIM supports better identification of potentially problematic areas, but AR allows users to more consistently determine why an area is problematic. This suggests an opportunity to use a hybrid BIM/AR approach for identifying and resolving maintainability considerations during the design phase. The findings from this work provide evidence to illustrate how AR and BIM may enable individuals with limited experience to be able to effectively think like facility managers in order to make better maintainability decisions during design to lead to a better building during operation.

1. Introduction

Maintainability, defined as restoring a component to its initial original design state [1], is essential for the long-term functionality of any building [2]. Maintainability can greatly impact the Life Cycle Cost (LCC) and functionality of a facility [3, 4], attributing to between 50% and 80% of a project's total cost [5, 6]. However, maintenance resources are continually decreasing while costs continue to increase [7], and facility managers (FMs) are facing an increasing frequency of design-related maintainability issues [8]. Improving maintenance processes is essential for the long-term success of any project.

The leading cause of operation and maintenance issues in facilities is the lack of maintainability considerations in the design phase, despite designers' best efforts [9]. Although designers attempt to make the best decisions possible, most operational problems in a facility are largely attributed to decisions made in the design phase [10]. For example, air handler vents need to be opened to change filters on a regular basis. If these units do not have sufficient clearance for the vent to be opened, changing filters will be difficult or impossible. This example illustrates the type of impact that design decisions can have on maintainability. Considering maintainability in design decisions can lead to more sustainable and cost-effective facilities during operation [11, 12].

One possible strategy to produce more maintainable facilities is to include FMs in the design phase [13]. While this can provide substantial value when executed correctly, researchers report potential problems with communication between FMs and designers [14]. Furthermore,

communication between FMs and designers is uncommon among industry teams [15]. This is partly due to the fact that facility management teams are frequently not formed by the time of design, making it impossible to get their input [16]. Challenges in communication between designers and FM teams can contribute to inadvertent downstream problems resulting from early project decisions.

Augmented Reality (AR) is a visualization technology that overlays virtual objects onto the real world [17]. The use of AR by designers to view models during design review sessions allows them to physically interact with virtual design concepts at full scale, similar to how they would actually interact with the physical building. This suggests a theoretical opportunity for AR to enable designers to better identify maintainability concerns by mimicking FM practices in maintainability-focused design review sessions, through the physical interactions afforded with AR.

In recent years, construction professionals have been getting more involved in the design phases of projects. In fact, BIM adoption among contractors is higher than among designers [18]. While this suggests BIM experience among construction companies, experienced construction professionals are diminishing due to the present labor shortage in North America [19]. This may illustrate the need for less-experienced individuals to be able to effectively leverage BIM and related technologies to provide critical input during design. This study aims to determine the extent to which individuals with limited construction experience are able to provide effective input using AR and more traditional BIM visualization formats when participating in maintainability-focused design review sessions.

This paper answers the following questions: What behaviors related to designing for maintainability are enabled while reviewing an existing design through AR as compared to Building Information Models (BIMs) through a traditional computer screen? How does reviewing the design using AR impact the recognition and evaluation of maintainability issues compared to BIM? These questions are addressed using an experimental procedure comparing the behaviors and performances of participants using AR and traditional BIM during maintainability design review sessions. The subsequent sections detail the research approach and findings.

2. Background

2.1. Designing for Maintainability.
Maintainability is largely impacted by design decisions, and these decisions often lead to inadvertent consequences during the operation of a facility [20]. The lack of maintainability considerations in the design phase is further evident when considering FMs' increasing costs [21]. A number of factors, such as accessibility, cleaning, and replacing components, and determination of parts are all affected by decisions made in the design phase [22]. These previous findings highlight the opportunity to improve the current design process in order to create more maintainable buildings.

Most areas that prove to be difficult to maintain are directly related to a lack of maintainability considerations in design [23, 24]. Checklists have been introduced to guide designers to create more maintainable designs in general [25] and also for specific systems [26]. Having a series of checklists to consider for each component may lead to cognitive overload while designing may lead to over-designing [27]. Methods to include maintainability considerations in design have been developed, but application of such methodology has proven to be difficult.

In response to the challenges associated with following detailed design checklists, other publications have suggested general maintainability criteria for design professionals to consider. For example, designers should ensure enough space to allow access and reach to components [12], reduce the general complexity of systems included [28], make the design more easily adjustable in the future if needed [29], and utilize longer-lasting components [12]. Despite advancements in designing for maintainability, maintenance problems due to building designs persist [9].

2.2. Building Information Modeling.
Building Information Modeling (BIM) involves the development of virtual representations of buildings with physical and functional features [30]. This includes information such as precise geometry, cost estimates, material inventories, and project schedule to which all participants refer throughout the process of design, construction, operation, and maintenance [30]. While BIM use has been increasing during design [31] and construction stages [32], researchers are just beginning to realize its benefits in the operations and maintenance stage [33]. BIM has been used to aid in developing maintenance plans, in order for maintenance personnel to locate and assess the location of work orders in facilities [34]. Kumar and Cheng studied the use of BIM to optimize space utilization and travel time in facilities [35]. Wetzel and Thabet developed a BIM-based framework to increase FMs' safety while attending to maintenance repairs [36]. Another effort used BIM and Construction Operations Building Information Exchange (COBIE) to aid with preventative maintenance for facilities [37]. Love proposed a learning mechanism to aid FMs in recognizing the value of BIM and its benefits in facility maintenance [38]. These studies illustrate the potential for BIM to offer value in operation and maintenance phases.

However, fewer studies have incorporated BIM in the design phase for FM purposes [39]. Wang illustrated the potential for BIM to support design for FM by enabling pathway optimization, energy management, and commissioning [40]. Despite this potential, viewing virtual BIM content for maintainability concerns can also be challenging, and maintainability issues can easily be hidden within the model [41]. These studies illustrate the potential for BIM to elicit early design feedback that can support operational needs, but it is not yet clear the extent to which BIM environments may effectively enable designers to think like end-users to identify problematic design elements in existing construction projects.

2.3. Augmented Reality.
Augmented Reality (AR) is a technology that enables virtual objects to be overlaid onto

the physical world, allowing the user to view them as if they were real [42]. AR has been shown to offer potential value in different stages of a construction project [43]. In pre-construction, an AR-based construction planning tool was tested instead of using 2D plans to reduce construction planning errors [44]. During construction, participants using AR were observed to be significantly faster in assembling electrical conduit than those using 2D plans, and they had fewer errors [45]. Yeh et al. studied AR for on-site information retrieval, in order to view construction drawing specifications instantly instead of using 2D plans [46]. AR was also used for equipment operation modeling to maintain safe and effective construction practices [47]. These studies illustrate how AR may support various performance gains related to construction tasks.

In addition to construction applications, researchers have also found merits to using AR technology in various maintenance and maintainability tasks. Zhou discussed the feasibility of using AR to rapidly inspect segment displacement during tunneling construction [48]. Lee utilized an AR interface that monitors real-time construction operation data of equipment to maintain efficiency on-site [49]. Other work demonstrated the use of an AR tool for FMs to access additional information that they may need while undergoing regular facility repairs and inspections [50]. AR has also been used for maintainability by assisting mechanics in removing and installing components, plugs, and fasteners in the manufactured product industry [51]. Schall et al. presented an AR system for aiding field workers of utility companies in outdoor maintenance tasks [52]. While AR is being increasingly utilized for maintenance during the operation phase, little effort has been made to assess the value of using AR to enhance maintainability considerations of the different components during the design phase. This paper addresses this knowledge gap.

3. Methodology

To study the behaviors of individuals with limited facility management experience when using AR and BIM during maintainability design review sessions, the researchers identified existing maintainability issues and developed a 3D model that aggregated those areas into a single space. The researchers then used an experimental methodology to compare students' abilities to identify design concerns in the same model when visualizing that content either with AR or with BIM on a traditional computer screen. Figure 1 provides an overview of the research methodology followed. The subsequent sections detail the procedure followed by the researchers.

3.1. Identifying Common Maintainability Issues.
The researchers collaborated with the facility management team of a large university to identify the most common maintainability issues encountered in built facilities that could have potentially been avoided with different design decisions. The researchers toured multiple facilities at the university, accompanied by the FM personnel responsible for maintaining each facility. The researchers noted and photographed the areas that the FMs considered challenging or impossible to maintain due to specific attributes of the design. Subsequently, interviews were conducted to determine the frequency of these problems in other facilities. Accessibility was the main cause of maintainability concerns, and four different types of maintainability issues were identified, as summarized in Table 1.

Theoretically, these recurring types of accessibility problems should be detected during maintainability-focused design review sessions. However, as evidenced by the frequency of observing these issues in practice, these issues are often missed during design, which lead to instances of unmaintainable building designs. Therefore, this research aims to study the extent to which AR enables less-experienced individuals to recognize critical maintainability concerns that are frequently missed in the current design process.

3.2. Model Development.
A 5-meter by 5-meter equipment room model was developed by the researchers for the purposes of this experiment. In the model, three types of maintainable elements were included: ball valves, push/pull valves, and air vents. Twelve total elements were included. Six of these incorporated maintainability problems that were reported by the FM team and the other six represented acceptable design scenarios. Of the six problematic areas, three corresponded to obstruction issues, and one corresponded to horizontal reach, vertical reach, and other ergonomic restrictions, respectively. The researchers chose to include more obstruction issues in order to more accurately represent the frequency of maintainability concerns, as reported by the FMs during prior interviews and site walks. After developing the model, it was shown to FMs, and they confirmed that the maintainable areas were in fact maintainable and that the nonmaintainable areas were in fact problematic. This process helped to validate that the building elements deemed to be problematic and not problematic were accurately categorized, according to current professionals. The resultant model is shown from two viewpoints in Figure 2.

All 12 valves and vents were numbered with unique identification numbers (IDs) to enable participants to clearly state which element they were viewing. The numbered IDs were not in any particular order and were not numbered one through 12 to avoid participants from being able to discern how many elements they should be seeing within the model. Designers would not know how many problematic elements they should be seeking during a model review, so the researchers intentionally did not tell participants how many they should be expecting either.

3.3. Developing AR Application.
After finalizing the model content, the authors began building the AR application. Theoretically, the authors could have elected to use virtual reality (VR) instead of AR, but VR does not intrinsically allow a user to be able to see his or her own body in the visualization experience. Instead, this may simulated through the use of an avatar. While it is possible that VR may
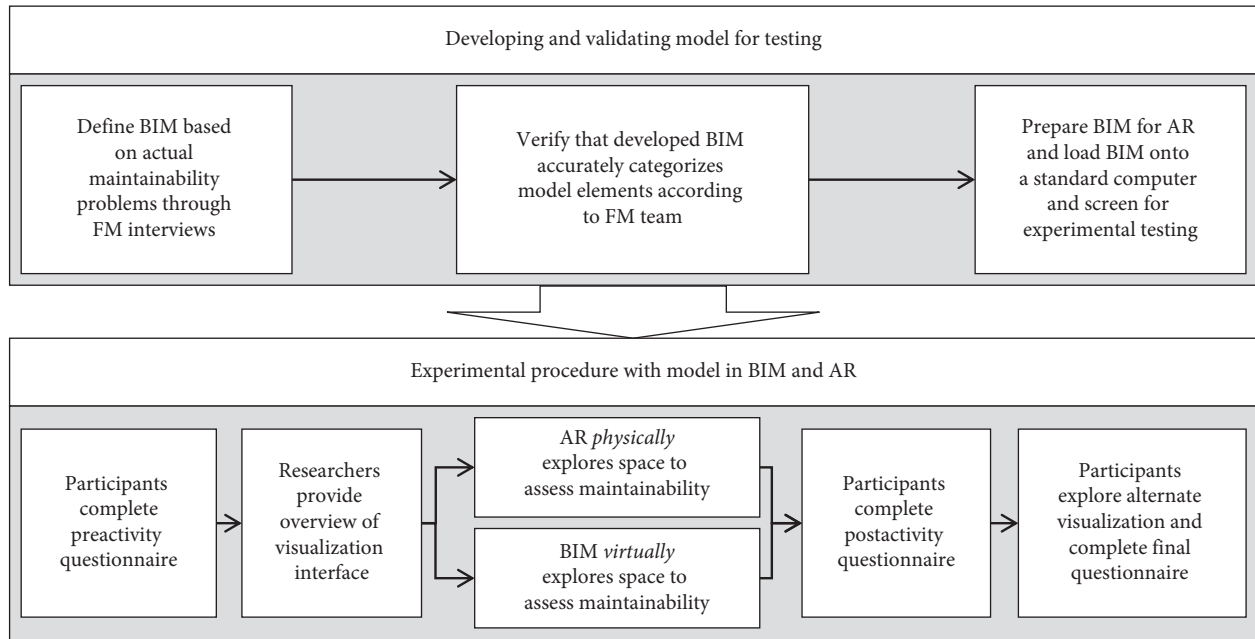
Figure 1: Model development and methodological approach followed by researchers.

Table 1: Accessibility categories and their definitions.

Categories	Definition
Horizontal reach	Areas that are difficult to reach on a horizontal axis, not intended to include instances where standard equipment would allow a FM sufficient access
Vertical reach	Areas that are difficult to reach on a vertical axis, not intended to include instances where standard equipment would allow a FM sufficient access
Obstruction	Areas that include components that block other components' range of motion during maintenance
Other ergonomic restrictions	These areas may result in FMs having limited maneuverability while maintaining the component

provide value to a maintainability-focused design review, the authors strategically targeted the unique physical engagement affordances of AR. This enabled them to determine the extent to which participants would physically experiment in the environment to perform the types of tasks that eventual FMs would be expected to perform and observe how that interaction may support the generation of relevant design for maintainability feedback.

For this work, the authors elected to use the Microsoft HoloLens, which is a head-mounted display (HMD) that allows users to visualize the design at 1 : 1 scale. This device uses infrared sensors to map users' surroundings and allows them to interact with virtual content overlaid onto their view. Furthermore, this HMD does not require a physical connection to a computer, which enables users to move freely in space.

The model was exported from the native BIM software to a FBX file, which was in turn imported into the Unity Game Engine for development for the intended AR device. Scripts were added in Unity to add control to the model. Four voice-based commands were integrated: "Higher," "Lower," "Reset," and "Stop." "Higher" moves the model downward to simulate the user going slowly upward, and "Lower" moves the model upward to simulate the user moving down. These functions were added to allow users to simulate the change in elevation and accessibility enabled by using a ladder. To allow users to choose their own desired elevation for exploration, a "Stop" function would stop model movement when this word was spoken. Finally, "Reset" enables the user to recalibrate the model into its initial position on the ground floor automatically. These commands allowed the participants to interact with the AR space in a safe manner, but also allowed them to view the space similarly to how a real FM might interact with the physical space.

3.4. Experiment Activity.
Participants were recruited from a senior construction management class at Arizona State University. The participants had at least two internships each and reflected the less-experienced target audience of this paper. The following sections detail the steps taken by participants throughout the experiment.

3.4.1. Preexperiment.
The participants were first given a consent form to permit their data to be used for research, in accordance with the authors' Institutional Review Board. Participants were then asked to fill a prequestionnaire. The questions involved in this work are included in Table 2.

After participants completed the questionnaires, they watched a video presentation that introduced the activity to them. During this video, the valves and vents included in the model were shown, and the function of each was
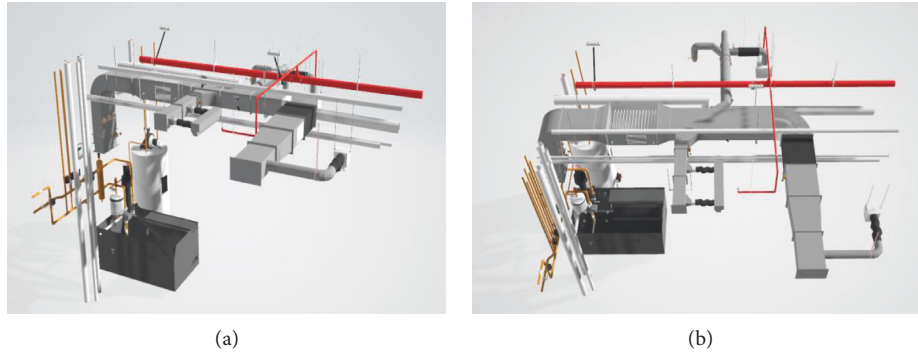
(a)   (b)

FIGURE 2: 3D model used in both visualization methods.

TABLE 2: Prequestionnaire questions.

Prequestionnaire questions (and response options)
(1) Have you been a part of a design review session before? (Yes/No)
(2) Have you been a part of a design review session that assessed maintainability before? (Yes/No)
(3) Do you have any experience in facility maintenance? (Yes/No)
(4) If you answered "yes" to the previous question, please specify your role and responsibilities during your experience. (Short answer)
(5) Do you have any experience using AR? (Yes/No)

demonstrated. For example, the way to open and close specific valves was shown. Additionally, the four categories of accessibility in Table 1 were explained to the participants. This helped to ensure that each participant understood what type of model element he or she was expected to locate and also that each participant could differentiate between the access concern categories that were defined.

Before starting the design review activity, a think-aloud protocol was also introduced to the participants. Participants were specifically asked to state what they were thinking throughout the activity. As participants identified numbered building elements, they were asked to state the number of the area they were exploring and then state whether the area was maintainable or not. If participants stated that a modeled element was not maintainable, they were asked to choose the accessibility category that they felt described the nature of the issue. If any participant did not state clear and complete information about a particular modeled element that they were exploring, the researcher intervened to ask for additional information as required. This protocol helped to illustrate the underlying thought processes performed by the student participants.

3.4.2. During Experiment. Each participant was randomly assigned to complete his or her design review using either Navisworks on a traditional computer screen or using the developed AR content. The BIM and AR models used the exact same model file (FBX format), which was exported from commonly used BIM software. This ensured that the specific content viewed by all participants was identical and only the format of that visualization changed. If the participant was assigned to the computer screen, the "walk", "zoom," and "orbit" commands in Navisworks were demonstrated. If the participant was assigned to use AR, he or she was assisted in wearing the headset, taught the four voice commands, and instructed on how to physically navigate the space to move in the virtual model. Figure 3 illustrates what the experimental space and user experience involved in this work. In both AR and BIM cases, the experiment began when the participant stated that he or she understood how to navigate the model.

Each participant was asked to navigate the virtual space in order to locate areas that included one of the numbered components (i.e., ball valves, push/pull valves, and air vents) in the real space, as illustrated in Figure 3. It was also made clear to the participants to discontinue the activity immediately if they felt any discomfort or dizziness. After locating one of these components, the participant stated the information required from the think-aloud protocol. The entire design review experiment was video- and audio-recorded, which allowed for subsequent analysis of results by the researchers.

3.4.3. Postdesign Review Activity and Alternative Visualization. After completing the activity using either visualization format, participants were provided with a postquestionnaire. The content of the questionnaire is included in Table 3.

When participants completed the questionnaire, they were shown the alternative visualization tool. If they originally viewed the model in AR, they were shown the model on a computer screen and vice versa. The participants were asked to briefly look through the model and consider a single instance of a valve or vent to familiarize themselves with the alternate visualization format. Based on their experiences with both visualization formats, a final questionnaire was given to the participants. The content presented in the questionnaire can be seen in Table 4.

The responses to these questions helped to illustrate the perceptions of the students regarding their preferences after they had an opportunity to explore both visualization formats.

3.5. Analysis. Three main data points were extracted from the design review activity: the number of areas that each participant found, whether each identified area was

(a)   (b)

FIGURE 3: The space used for the augmented reality environment: third person and first person views.

TABLE 3: Postquestionnaire questions.

Please indicate the extent to which you agree with the following statements (0 = strongly disagree and 10 = strongly agree)
(1) It was easy to find the location of all targeted components
(2) I was able to identify which of the target elements posed a maintainability concern
(3) I provided effective suggestions to improve maintainability

TABLE 4: Final questionnaire questions.

Please indicate the extent to which you agree with the following statements (0 = strongly disagree and 10 = strongly agree)
(1) Augmented Reality can help users think more like facility managers
(2) I would prefer to use AR over traditional BIM in designing for maintainability
(3) AR was easier to use than BIM (on computer screen)
(4) (Choose one) If I were to conduct another design for maintainability design review session I would use:
(i) Augmented Reality (AR)
(ii) BIM (on computer screen)
(iii) AR and BIM (on computer screen)
(iv) Others

considered by the participant to be maintainable or not, and the accessibility category in which the participants placed the areas, if applicable. The data recorded during the experiment were inputted into a spreadsheet, which allowed for sorting and organizing the data points. The data points were then uploaded onto SPSS for statistical testing. The two visualization tools were compared according to their ability to allow users to locate areas and navigate the space, make effective maintainability decisions, classify problematic areas into one of the four categories, and avoid false identification of areas as nonmaintainable. False identification of an area is an instance when an area is located and reported as problematic by the participant even though it did not receive any maintainability concerns from the FMs interviewed. A representation of the analysis structure and corresponding result section is illustrated in Figure 4.

The videos collected from the design review activity were exported into behavioral coding video analysis software. The videos of the participants using AR were analyzed for two specific sets of behavior: physical interactions and verbal interactions with the model. A physical interaction

with the model consisted of any movement the individual made relative to the model, such as using their arms to reach out and gauge distance between themselves and a virtual object. A verbal interaction was the use of any of the voice commands within the AR application. The data extracted from the analysis process was imported into a spreadsheet. The findings relating to performance and perception are presented in the following section.

4. Results

The students involved in this work had completed three years of academic coursework related to construction management and were in the process of completing their fourth year. Their academic program of study includes courses related to construction estimating, planning and scheduling, materials and methods, basic structural analysis, building systems, and other general education courses. Beyond their academic background, the participating students also completed at least one industry internship, with most students having completed more than this, which provided some basic industry experience; to guide their behavior, 3.2% of the sample had taken part in a maintainability-focused design review session prior to participating in this research. Only 15.9% of the sample had used AR at least once before, and 11.9% of the sample had previous experience in the facility management field. The low percentage of participants with experience in design review for maintainability and AR usage represent a novice participant sample, while participants' background and experience in construction indicate a basic understanding in the processes of designing, constructing, and operating facilities.

4.1. Performance. The two modes of visualization were compared according to four criteria: (1) ability to locate areas that would require maintenance; (2) ability to enable users to make decisions about whether the area is maintainable or not; (3) ability to correctly assess the type of accessibility issue; and (4) ability of users to avoid false identification of maintainability problems. Given the categorical nature of the independent variables, the researchers used cross-tabs and corresponding Pearson chi-square tests to identify statistically significant relationships between the visualization medium and criteria of concern. The following subsections detail the findings in each criterion.
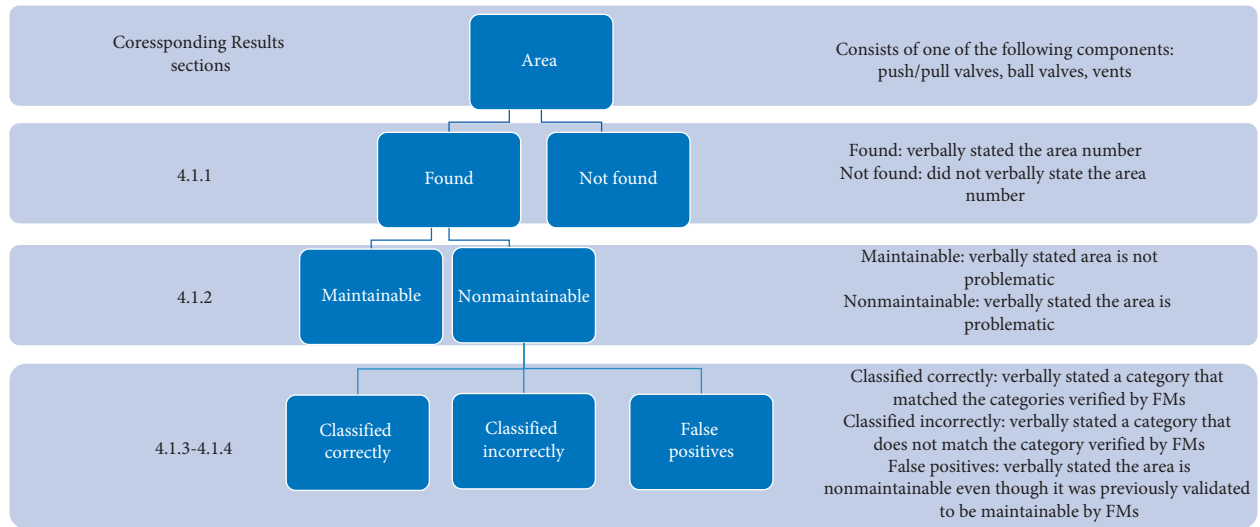
FIGURE 4: Steps for analyzing design review session.

4.1.1. Effect of Visualization Medium on Locating Areas. An area is considered to be located when the participant verbally states the selected area's number. Table 5 shows the number of areas and percentage found using each visualization medium.

When using BIM, the participants found 81.6% of the numbered areas in space, compared to 73.7% of the areas when using AR, and the difference is statistically significant according to the chi-squared test (P value <0.05). This indicates that users are significantly better at finding areas of interest in space using BIM on a traditional computer screen compared to when using AR.

This finding may be explained by the differences afforded through BIM and AR navigation. While the participant has to physically walk through the space when using AR to see it in its entirety, he or she can quickly pan and zoom through a BIM on a computer screen to achieve the same functionality, making space exploration significantly easier on a computer screen. This may explain the comparative ease of identifying targeted building elements in BIM over AR.

4.1.2. Effect of Visualization Medium on Identifying If Areas Are Accessible. After locating the points, the participants were asked to decide if the area they had identified was maintainable. Areas that had maintainability issues were considered correctly identified when participants verbally stated that an area was unmaintainable. Areas that did not have maintainability issues were considered to be correctly identified when participants stated that the area was maintainable. Table 6 shows the number of areas identified correctly in each medium.

When a point was found, it was correctly identified 82.4% of the time when using BIM on a screen, compared to 84.3% of the time when compared to AR. While this illustrates a numerical difference, there was not sufficient evidence to indicate a statistical difference between these performance findings according to the Pearson chi-square test (P value >0.05). Therefore, this does not provide evidence that either mode of visualization is better for determining whether something is maintainable or not.

4.1.3. Effect of Visualization Medium on Identifying the Type of Accessibility Issue. If participants locate the area and decide it is unmaintainable, they are then prompted to categorize the area into one of the accessibility subcategories. The number of correctly classified points in each medium can be seen in Table 7.

When a point was correctly identified as unmaintainable, a participant was able to correctly classify the reason 80.1% of the time when using AR, compared to 73.7% of the time when using BIM on a traditional computer display, and the difference is significant at the 95% confidence level (P value <0.05).

This indicates that participants using AR were significantly better at classifying maintainability problems. This could be attributed to the physical interactions enabled by using AR, where the participant can check whether a system is placed in the correct position in reference to the real environment. This finding is especially noteworthy because it illustrates that the physical exploration afforded through AR does not only provide a novel experience, but that this experience actually impacts students' ability to evaluate why a given building component works or not more than BIM on a computer screen.

4.1.4. Effect of Visualization Medium on Avoiding False-Positive Identification. False-positive areas represent areas that were verified as being maintainable by the FMs, but were identified as being nonmaintainable by the participant during the design review activity. Participant performance in avoiding false-positives in both visualization media was analyzed.

Table 8 shows the count and percentages of false-positives identification.

TABLE 5: Effect of visualization medium in locating areas and corresponding chi-square results.

| Medium | Count, % within medium | Locating areas | | Total | Pearson chi-square P value |
		Not found	Found		
BIM (on-screen)	Count	73	323	396	
	% within medium	18.4%	81.6%	100.0%	0.004
AR	Count	98	274	372	
	% within medium	26.3%	73.7%	100.0%	

TABLE 6: Effect of visualization medium on identifying accessibility and corresponding chi-square results.

| Medium | Count, % within medium | Correct identification | | Total | Pearson chi-square P value |
		Incorrect	Correct		
BIM (on-screen)	Count	57	266	323	
	% within medium	17.6%	82.4%	100.0%	0.262
AR	Count	43	231	274	
	% within medium	15.7%	84.3%	100.0%	

TABLE 7: Effect of visualization medium on maintainability classification.

| Medium | Count, % within medium | Correct classification | | Total | Pearson chi-square P value |
		Incorrect	Correct		
BIM (on-screen)	Count	70	196	266	
	% within medium	26.3%	73.7%	100.0%	0.046
AR	Count	46	185	231	
	% within medium	19.9%	80.1%	100.0%	

When a participant was using AR, he or she falsely identified only 11.8% of maintainable areas as unmaintainable. Conversely, when a participant was using BIM on a traditional computer screen, he or she falsely identified 24.7% of maintainable as unmaintainable. The difference is significant at the 95% confidence level. This suggests that using AR reduces the need to review correctly designed areas in a given space, further increasing the productivity of the reviewers.

Furthermore, when using AR, participants verbally and/or physically interacted with the model in 96.8% of the areas considered. In 74.2% of the cases, the participants chose to invoke verbal interactions, allowing them to safely simulate actions that would have been undertaken by the FM, such as climbing a ladder. In 90.3% of the cases, the participants physically interacted with the model (i.e., reached out to physically touch virtual building components in an attempt to mimic the types of actions that FMs would perform). This highlights the natural inclination of participants to physically interact with the model, taking further advantage of the unique opportunities enabled by this mode of visualization.

These interactions, especially the physical ones, are unique to this type of visualization and may be the reason for the enhanced performance compared to viewing the same model on a computer screen. Similar to the results on classifying building elements, this suggests that the interactions afforded in AR allow participants to more effectively evaluate design elements for maintainability.

In the prequestionnaire, each participant was asked to identify whether he or she had any experience participating in design review sessions and whether any of those sessions were specifically maintainability-focused review sessions. Furthermore, participants were asked if they had any experience in facility management or with using AR prior to this research activity. While the responses illustrated some variation in levels of experience among participants, none of these individual attributes indicated any statistically significant effects on the performance. In other words, when assessing the ability of participants to find areas in the model, correctly identify whether the areas are maintainable or not, and correctly classify areas deemed to be unmaintainable, none of the individual attributes of participants had an impact on their performance.

4.2. Perception. The participants were asked to rate their performance on a Likert scale from 1 to 10, with 10 being the highest level of agreement with the statements, after completing the activity. The questions and average response per communication medium are detailed in Table 9. The participants seem generally comfortable using both viewing media, with bias towards AR, especially when asked about the ability of identifying maintainable areas. This is especially noteworthy because it illustrates that their perception may not necessarily match their behavior. For example, students in the AR group generally reported higher perceived ability to find components, but comparatively lower ability to determine which components posed maintainability concerns, even though this finding is in opposition to the behavioral coding analyses.

Table 8: Effect of medium on false-positive identification and corresponding chi-squared results.

Medium	Count, % within medium	Correct identification		Total	Pearson chi-square P value
		Incorrect	Correct		
BIM (on-screen)	Count	37	113	150	
	% within medium	24.7%	75.3%	100.0%	0.0035
AR	Count	14	105	119	
	% within medium	11.8%	88.2%	100.0%	

Table 9: Postquestionnaire-perception results.

Statement	AR average	BIM average
It was easy to find the location of all targeted components	8.65	8.13
I was able to identify which of the target elements posed a maintainability concern	8.69	9.06
I provided effective suggestions to improve maintainability	8.32	8.13

Table 10: Alternative visualization questionnaire results.

Statement	Mean agreement (1–10)
Augmented reality can help users think more like facility managers.	9.1
I would prefer to use AR over traditional BIM in designing for maintainability	7.63
AR was easier to use than BIM (on computer screen)	7.17

After using the second visualization medium at the end of the session, the participants were given an additional questionnaire. This helped to illustrate the preference of students to use one mode of visualization over the others. Table 10 summarizes the questions and average answers of the participants. The responses were rated on a Likert scale from 1 to 10, with 10 being the highest level of agreement.

In general, the participants agreed that AR can help users think more like facility managers in designing for maintainability. In fact, when asked to choose a visualization medium that they would like to use for a design review session, 93% of the respondents stated they would use a combination of on-screen BIM and AR. Participants stated that while viewing the same area in AR in comparison to BIM, they changed their classification of the area, stating that now that they could explore the space with reference to their own bodies and the surroundings they were able to identify possible accessibility complications in the BIM. The results indicate that participants realized that they were able to conduct more accurate inspections of the areas using AR, but may have been inclined to use both visualization methods due to the navigation capabilities of BIM.

5. Discussion

AR and BIM on a computer screen both showed advantages to users' performance. BIM on a computer screen allowed users to locate components in the model more effectively, while AR enabled users to identify how or why an area posed maintainability issues more accurately than with BIM on a computer screen. Furthermore, viewing the model in an AR environment enabled the users to avoid false-positive identification more than with BIM on a computer screen. It is also noteworthy that no participant felt any discomfort or dizziness while conducting the activity. In addition to the behavioral evidence that illustrates the potential value offered by both modes of visualization, the students also reported perceived value to both formats for various reasons. Therefore, in order to capitalize on the observed behavioral

affordances and perceived advantages of each visualization method, the researchers propose a hybrid visualization approach to performing maintainability-focused design review sessions. Figure 5 illustrates the steps involved in the suggested hybrid method.

First, the researchers assume a 3D model of the designed space is either developed or obtained by the review team. A user would then start by exploring the space using a traditional computer screen, locating any areas that may seem problematic. Exploring the model on a screen initially will mitigate AR's current limitations in rendering and navigating large spaces and enable the user to automatically query the model to quickly locate similar types of devices, such as valves and vents, that may present problems.

Once the areas are located, the user can then export the model to an AR viewing environment. In AR, he or she can inspect each area, leveraging the physical and verbal interactions uniquely afforded by AR. Then, he or she would identify whether each area is maintainable or not. While evidence collected in this work did not indicate a performance difference in the ability to determine whether or not elements are problematic, AR enabled users to more effectively avoid falsely identifying acceptable areas as problematic. Therefore, this approach would capitalize on the benefits observed by users of AR.

For all the areas that the user determines that are unmaintainable, he or she would classify them into one of the four categories previously defined. Classifying the unmaintainable areas may further facilitate the process of rectifying the errors by offering a descriptive explanation of the reason why the area is not maintainable. This would remove the need to speculate during the design revision phase.

Once all the unmaintainable areas are identified and classified, the user may use either an AR or a BIM environment to discuss solutions. An external stakeholder can also be added to the discussion at this point, where AR can allow him or her to explore the design by simply walking and looking around, regardless of previous experience.
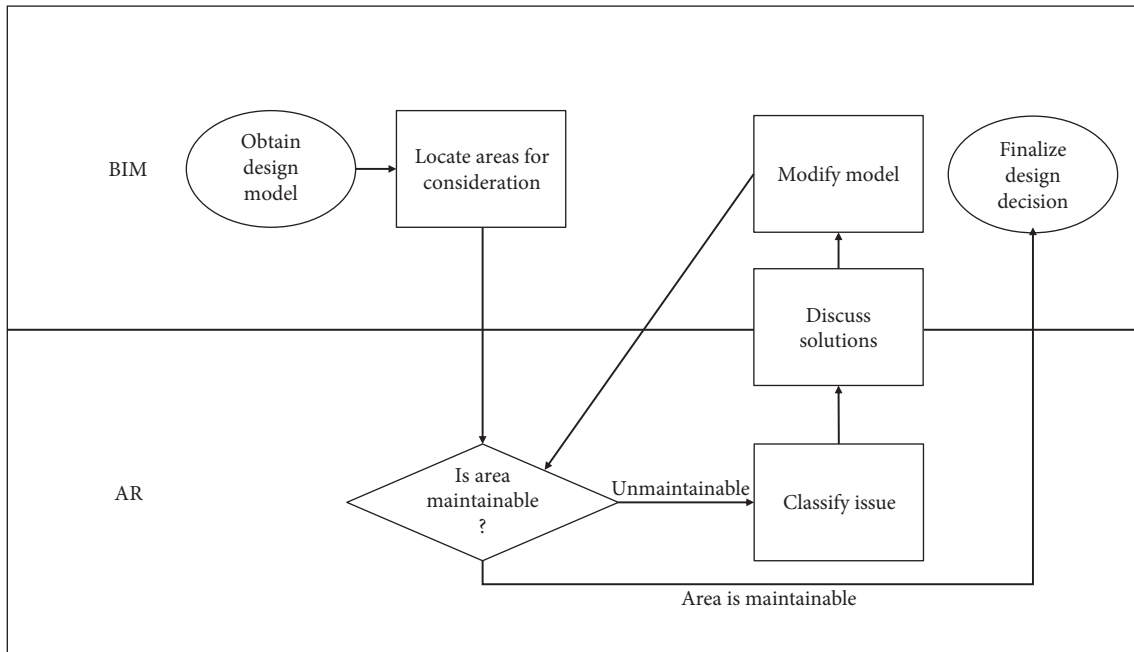
FIGURE 5: Hybrid visualization approach.

Once a solution is chosen, the model is rectified in a traditional BIM environment, and the model is once again exported to an AR environment, and the newly adjusted areas are checked once again for maintainability issues. This loop would continue until no maintainability issues can be found. This may be difficult to execute if the design is not adequately detailed, which is why this approach is best used during late stages of design. At that point, the model can then be finalized in a traditional BIM environment. This process provides an evidence-based approach to maintainability-focused design review sessions, but should still be independently tested to validate its effectiveness in the context of actual maintainability design reviews.

6. Limitations

There are a few limitations to the work presented in this paper related to the process and the model explored. First, during this design review session, the participants were prompted to look solely for maintainability concerns related to certain systems while exploring the space. In most actual design review sessions, designers do not focus only on maintainability of certain systems. They also consider other, nonmaintainability-related factors, such as the overall design of the room, the fit of the equipment, constructability, and other concerns depending on the type of the project. Therefore, this focus on maintainability concerns for certain building components could have impacted the ability of the participants in this work to identify maintainability concerns in design. While this may illustrate a practical limitation based on current design review practices, it also illustrates evidence to further suggest value to changing the way that maintainability reviews are conducted in order to leverage the unique affordances provided by AR and BIM when designers specifically consider the needs of FM

professionals. Fully adopting this type of approach could lead to a decrease in design-related maintainability issues.

Additionally, the researchers designed the space used in this experiment by aggregating a number of areas from different existing facilities that were observed to be difficult to maintain. While both maintainable and nonmaintainable areas were included in the model, the density of the components in the overall space could potentially be higher than other equipment rooms typically reviewed in design sessions. This approach allowed the researchers to collect statistically significant samples by allowing each participant to find (or fail to find) known building components in a confined space, but it may not exactly represent the density of maintenance concerns experienced in typical design review sessions. While this should not influence the users' ability to classify components, it could theoretically allow participants in this work to locate model components more easily. This limits the extent to which authors can claim that others would find similar percentages of elements in other models; however, the proposed hybrid BIM/AR review strategy would negate this issue. If future researchers and practitioners use BIM on a computer screen to quickly identify specific building components, through automatic model queries, they could identify all points of interest regardless of model size or density. Then, they could use AR to quickly investigate the maintainability of each of the identified building components.

7. Conclusion

The researchers aimed at understanding the behaviors of individuals with limited facility management experience when using AR in comparison to on-screen BIM for maintainability-focused design review sessions. The researchers followed a comparative experimental approach,

where half the participants used on-screen BIM and the other half used AR to locate areas, identify whether they are maintainable, and classify the maintainability problems using a previously defined paradigm. Participants that used BIM on a traditional computer screen were significantly more effective at locating relevant building components in space. However, by leveraging the physical interactions enabled by AR, the participants were more effective at identifying whether an area is maintainable or not and significantly more effective at classifying maintainability issues and reducing false-positive observations.

The researchers propose a hybrid visualization method for maintainability-focused design review sessions, which capitalizes on the benefits of both BIM on a traditional computer screen and AR visualizations. Using this method, a user would start by exploring the space on a computer screen to locate the areas of interest. Then, he or she would use AR to identify whether the previously located areas are maintainable and classify the maintainability problem when appropriate. Using immersive and interactive visualization approaches can enable inexperienced individuals to make more maintainable designs, especially considering the difficulties of incorporating FM input and maintainability criteria during the design phase.

The contribution of this work is in providing evidence of the differences in behaviors and decision-making observed by individuals with limited facility management experience when considering maintainability. Furthermore, this work contributes a new hybrid approach to using BIM and AR in conjunction to capitalize on the unique affordances of both technologies. These contributions will allow future researchers to target specific user behaviors related to designing for maintainability and will also allow them to implement the proposed hybrid BIM/AR strategy to make better-informed design decisions to support maintainability.

Data Availability

The data used in this research are based on observations made during an experimental procedure with human subjects. These data are protected by the Institutional Review Board (IRB) at Arizona State University (ASU) and cannot be divulged publicly. Aggregated data are shared in the manuscript to support the conclusions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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