BIM Driven Retrofitting Design Evaluation of Building Facades

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Figure 1: (A) A demonstration of our AR-BIM framework that enables designers to design facades in-situ for retrofits (The white facade shown is generated by our AR system.) (B) the four major base facade design alternatives available for review. (C) visualizes an alternative daylighting plane view our BIM-enabled facade designs provides to the study participants.

ABSTRACT

Building facades are components that shape a structure's daylighting, energy use, and view factors. This paper presents an approach that enables designers to understand the impact that different facade designs will have over time and space in the built environment through a BIM-enabled augmented reality system. The system permits the examination of a range of facade retrofit scenarios and visualizes the daylighting simulations and aesthetics of a structure while retaining function and comfort. A focus of our study was to measure how participants make decisions within the multi-objective decision space designers often face when buildings undergo retrofitting. This process often requires designers to search for a set of alternatives that represent the optimal solution. We analyze the decision-making process of forty-four subjects to determine how they explore design choices. Our results indicate the feasibility of using BIM-enabled AR to improve how designers make informed decisions.

CCS CONCEPTS

• **Human-centered computing** → **Mixed / augmented reality**; • **Computing methodologies** → **Mixed / augmented reality**.

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KEYWORDS

BIM, retrofitting, augmented reality, AR, built environment

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1 INTRODUCTION

In the built environment, retrofitting structures is a growing challenge for the *architecture, engineering, and construction* (AEC) industry. *Retrofitting* is a construction process that changes the function and structure of a building, increasing a structure's lifespan, preserving historical elements, and minimizing waste [31, 40]. This process ultimately provides greater environmental sustainability and additional financial benefits. Retrofitting a facade is one main approach to improve daylighting and energy consumption. Building facades act as a shield and a gateway toward integrating a structure with the surrounding environment. The key challenge in facade retrofitting is considerable uncertainty about how various facade design decisions will impact the overall building performance. These choices require trade-offs between conflicting goals, such as reducing glare while increasing outside views.

There are few tools and processes that permit a designer to interact in a 3D spatial environment to design and evaluate retrofitting options while promoting human-centric function. This paper examines how augmented reality (AR) and building information modeling (BIM) data can help stakeholders visualize and understand facade retrofitting choices. We designed a study where participants used a BIM-enabled AR *Facade Retrofitting Embodied Design* (*FRED*) system [54] to examine facades immersively in-situ (Figure 1(A)). *FRED* provides interactive daylighting visualizations and energy use feedback (Figure 1(B)(C)). This system permits an embodied (engages both body and brain) and enactive (free movement through the space) experience that connects each facade design with the impact of its choice upon a space allowing the observation of the impact of the facade choices for the early-phase retrofitting design process.

In a traditional design process, building elements are frequently planned in an unconnected manner. Architects leverage parametric digital modeling to optimize facades by automatically tuning parameters such as the rotation, number, and location of fenestration elements [18]. Parametric design tools discover a *set of optimal designs* in a short time frame [18, 51] greatly narrowing the solution space [20, 29, 33], but rarely leading to a single optimal choice [24]. Instead, parametric design tools typically provide several options for these multi-objective optimization problems. Designers are often faced with trade-offs between multiple conflicting variables, without producing a single correct solution. Additionally, no one understands the spatial functional impact these new facades will have in the space itself. For example, adding facade elements can increase visual comfort (reduced glare) and increase energy performance, but doing so reduces the aesthetic qualities and views of the outside environment. Understanding how these trade-offs impact people is critical when creating human-centric spaces.

Therefore, this paper examines how an augmented decision support framework FRED can enable architects, engineers, and facility stakeholders to understand both their design and its daylighting performance implications when they conflict with human-centeric design perspective. Our main results indicate that those using *FRED* successfully made a greater number of optimal facade design choices even though they were novices unfamiliar with the effects facades could have upon the interior environment. Our data post hoc analysis revealed deeper insights into the decision-making processes, specifically the differences in design choice exploration between high and low-performing participants. These results reveal the impact BIM-enabled AR has on selecting a facade that is a solution to multi-variable objective optimization in the built environment.

2 BACKGROUND

Buildings act as our connection to the external environment [13], serving as housing, centers for health, education, and employment as well as providing avenues for entertainment. However, aging buildings present a growing sustainability challenge [7] within our larger waning infrastructure [45]. Retrofitting is commonly performed to improve the energy efficiency, visual daylighting comfort, and functional usability of buildings [16], but these retrofitting processes lack rigorous study. A building retrofit project often saves time and money, as well as limiting landfill waste [31, 40]. Facades control how a building responds to indoor and outdoor environmental conditions and are often a main retrofit focus. [56]. Designing facades that balance these indoor and outdoor needs is a challenging process, as it is a multi-objective optimization process with conflicting goals [34, 64].

2.1 Facade Retrofitting Design

Facade designs. These building components protect from solar radiation, glare, and heat gain. Typical facade designs include *brise soleils*, *fins*, *louvers*, *tinting*, *awnings*, and *fritting*. Figure 2 shows four distinctive facade types we study in this paper. By designing spaces to use natural daylighting, buildings achieve the desirable interior lighting levels without relying on electrical lighting [14]. Natural daylighting can reduce tiredness and improve the physical health of building occupants [6]. However, increasing a building occupant's view outside can compromise its energy performance.

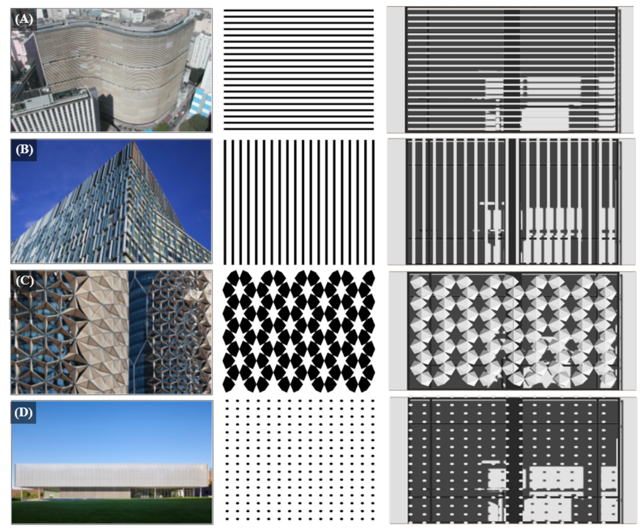

Figure 2: Visualization of shading facade designs: (A) Edifício Copan Building, featuring horizontal concrete louvers (Oscar Niemeyer); (B) Blue Fin Building, featuring vertical fins (Allies and Morrison); (C) Al Bahr Towers, featuring a kinetic shading system (AHR); and (D) JCCC Fine Arts and Design Studio, featuring fritting (BNIM).

- **View factor.** A *view factor* is the amount of unimpeded glazing to the surrounding exterior environment. Shading devices should minimize their impact on interiors to view external landscapes. As a facade occludes this view, the percentage of the view factor decreases based on the percentage of the surface area of glazing covered.
- **Daylighting.** Lighting levels approximately 100 to 3000 or 5000 lux (*ASHRAE 90.1-2019: Lighting Standards*) daylighting in a working space [2, 19] depending on the type of work being performed in the space. Some variance is acceptable with daylighting because of greater occupant glare toleration when compared to electrical lighting [49].
- **Visual comfort.** Glare is determined to be a factor when lighting exceeds acceptable levels and causes discomfort to an occupant. We consider the visual comfort metric of the environment and visualize a daylighting simulation of the space (Figure 1(B)(C)). This allows users to understand areas of acceptable working daylight and potentially problematic areas of both glare and insufficient low lighting.

Building Information Modeling. BIM supports the development of a digital workflow that permits the organization and access to vast amounts of documentation, coordination, and control during the lifespan of a structure [59]. BIM data includes: 3D digital models, digital blueprints, photographs, LiDAR scans, maintenance work records, and component sheets. Traditionally, BIM has been primarily used at the start of a new construction project and its potential in a structure's retrofitting is comparatively underdeveloped and an active area of research [53]. This paper focuses in the incorporation of retrofit designs into structures with well maintained BIM data.

2.2 Related Work

Role of AR in the AEC industry. Augmented reality systems provide support for evaluation of designs by permitting the overlay of information on their surroundings [15]. The foundations of AR construction and maintenance systems were laid by Steven Feiner et al. [21], who created documentation systems [28] that could overlay information upon the operator's environment [61]. AR systems have been proposed for knowledge-based maintenance and repair [12, 47], "X-ray vision" (i.e. projecting hidden building elements) [61], communication [4, 5, 26], and instructional guidance for construction, inspection, and renovation [61], assembly tasks [48, 58], and safety training [38]. Stakeholders benefit from such a system because it enables them to gain a holistic understanding of the retrofit project, and how it fits within the existing built environment [44, 48, 57]. Being spatially situated enables contextualization of how a design will avoid construction challenges and properly integrate the space [32, 36], building panels [52] and even thermal systems [22].

Role of AR-BIM in the AEC industry. BIM data encompasses the information of a building's lifecycle [9, 55] and enables effective visualization of expansive amounts of data [1, 17]. Additionally, BIM data presented in AR systems can provide a more accurate alignment of virtual elements. BIM's difficult workflows make it challenging to integrate into the design process [30], but AR can serve as a bridge alleviating these issues and increasing interaction [23]. AR provides users direct integration of BIM fostering collaboration [35]. AR interfaces for the AEC can support an architectural concept through design [62], building construction [42], and ultimately maintenance [28]. The traditional design process is enhanced by these 3D visualizations [1], 3D augmented geometry [46], 3D sketches [37], and freehand building design [39].

Grounded Cognition and design decision-making processes. The *embodied* functionality of AR permits situated spatial understanding and mechanisms for interactions and exploration of affordances [25]. Activating kinesthetic sensorimotor body interaction is vital to cognition [10]. Activating spatial body interaction is vital to cognition [10]. *FRED* uses "*4E*" cognition (embodied, embedded, enactive, and extended) as its theoretical foundation [43] for retrofitting facades spatially situated in the aesthetics, culture, emotion, and experience of architecture [41, 50]. When evaluating facades, it is critical to understand how AR helps decision-making processes. This work compares how participants studied and chose their facade design [3, 63] provided by *FRED* [54]. This analysis provides insight into their decision-making efficiency and how much time they spent considering optimal and poor choices.

2.3 Optimal Facade Design

This study addresses three main objective design variables: (1) *view factors*, (2) *daylighting*, and (3) *visual comfort*. Participants need to realize the impact their choices will have when grappling with multi-objective optimizations [27]. Facade designs can be changed and plotted (Figure 3) to understand their impact on this larger three-parameter solution space.

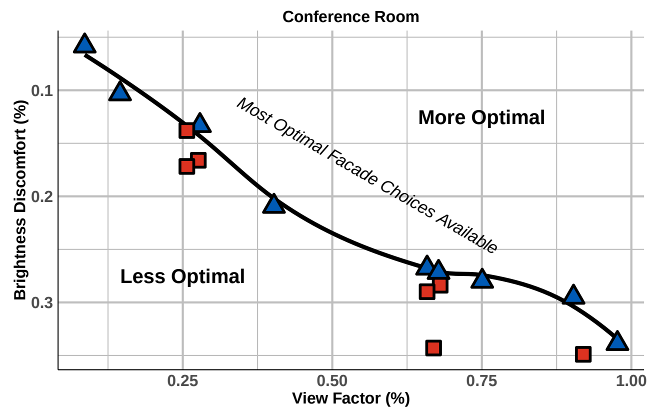

Figure 3: Visualization of the facade design parameter space. The upper rightmost point is represents the most optimal design. We rank and categorize the closer design choices *good* (blue triangles) and the further points *poor* (red squares).

An ideal solution would optimize all considered variables (Figure 3). However, since some of the variables are coupled inversely in a non-linear fashion (increasing view factors and decreasing visual comfort), this optimal point is not reachable. The *Pareto optimality* [8] can provide the best reachable designs to limit solutions and objectively compare facade choices. FRED provides sixteen choices ranked and categorized based on their *Pareto optimality* (Figure 3 blue triangles (good) and red squares (poor)) enabling an objective measure to test. The *Pareto optimality* of the facades was calculated by plotting their visual comfort and view factor. Facades were ranked based on the distance to the top right corner of Figure 3.

3 METHODOLOGY

In this section, we describe the experiment we conducted to understand the impact BIM-enabled AR has on increasing the selection of optimal solutions, and better understanding the AR-enabled decision-making processes. The primary research questions this paper explores are:

- **[RQ1]:** Does BIM-enabled AR increase more optimal facade design choices relative to their multi-objective optimization criteria faced in retrofitting?
- **[RQ2]:** Does BIM-enabled AR increase decision-making efficiency allowing participants to discriminate optimal and non-optimal facade choices relative to their multi-objective optimization?

To examine these questions, we designed a study where participants used a BIM-enabled AR Facade Retrofitting Embodied Design (*FRED*) system [54] to examine facades immersively in-situ in two

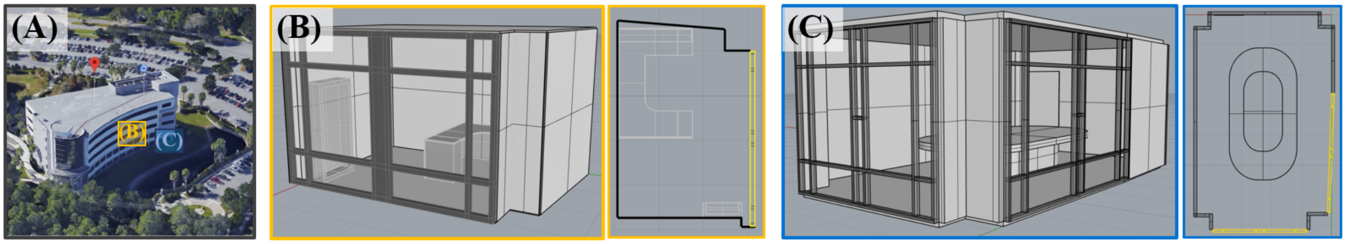

Figure 4: (A) is the location of our five-story building in the southeast U.S. in climate zone 9b with unoccluded exterior views; (B) is the third floor office room and floor plan; (C) is the first floor conference room and floor plan.

spaces 1) a standard office (with one wall of windows) or 2) a conference room (with two walls of windows) with the task of optimizing the space's aesthetics, view factors, daylighting, and visual comfort.

3.1 Participants

We recruited forty-eight student (48) participants (25 male, 19 female, age 18-45, M = 22.8, SD = 5.7) affiliated with our university (both undergraduate and graduate), who volunteered for the study. Four (4) participants' data were excluded from analysis as they did not follow directions during the experimental procedure (they remained seated) or experienced software data collection errors leaving a final pool of 44 participants, with 22 randomly assigned to each of the two (2) experimental conditions. All participants had normal or corrected-to-normal vision and reported no motor or sensory deficits nor had previously experienced motion sickness.

The experimental protocol was approved by the university IRB with each participant consenting to the protocol and were treated in accord with the ethical guidelines of the *American Psychological Association and the Declaration of Helsinki*. We asked our participants to rate their experience using a 7-point scale (1 = *novice/not familiar*, 7 = *expert/very familiar*) with AR (M = 2.25, SD = 1.48), VR (M = 3.36, SD = 1.66), using a computer for work (M = 6.81, SD = 0.57), virtual modeling software (M = 1.95, SD = 1.51), with no one reporting experience with AR-BIM visualizations. We also inquired if any had experience with construction/retrofitting activities (M = 1.68, SD = 1.22), and four (4) participants reported participating in a major retrofit of a building. Participants were asked if they were familiar (yes=1/no=0) with typical facade designs: *louvers* (M = 0.11, SD = 0.32), *fins* (M = 0, SD = 0), *fritting* (M = 0, SD = 0), and *brise soleils* (M = 0, SD = 0). All participants were asked to rate video game experience on a 10-point scale (M = 7.18, SD = 2.72).

3.2 Materials

Experiment setup. Participants were situated in a room within a five-story building in the southeast U.S. in climate zone *9b* with unoccluded exterior views. They were fitted with a *Microsoft HoloLens 2* (FoV: 52°, (diagonal) resolution: 1440 X 936 per eye , refresh rate: 60 hz). An *Apple iPad* (8th generation) was used to display and answer questionnaires composed using *Qualtrics* survey software. The BIM and interaction software used *Unreal Engine 4.25* with *Datasmith*, and *Autodesk Revit 2020* and *Rhino 6* to create digital models. A short training video was provided to explain the Facade task and the multi-objective variables being optimized (view factors, visual comfort, and daylighting). Additionally, participants were verbally instructed and encouraged to freely explore the room as they explored the facade designs and their impacts.

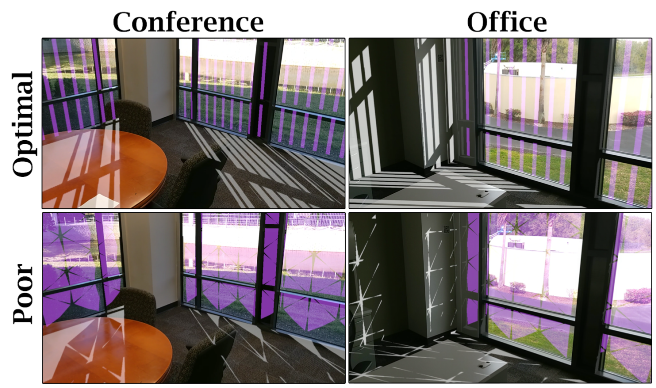

Figure 5: Example of the augmented environment for the study. 22 participants were placed in the conference room, and 22 were placed in the office room. The top is example of *optimal* solutions, the bottom row *poor*.

Augmented environment. The participants were situated in either a standard second floor office space (Figure 4B) with one wall of floor-to-ceiling windows, or a conference room on the first floor (Figure 4C) with two walls of windows. This permitted a between-subject analysis. They stood and viewed the room as the facades and their daylighting/shadows were augmented by the *HoloLens 2*. The experimental spaces faced north and were not subject to any direct sunlight, only diffuse skylight. The experience simulated a southern direction to test how the direct daylighting would affect facade choices. Augmented daylight and shadows were simulated with the Unreal daylighting system to provide plausible augmented direct solar and shadow effects in the space. This changed based on facade choice. Participants could also toggle an environmental overlay that showcased quantitative lighting levels along the floor in the form of a solar radiation heatmap (Figure 1C). Raising their left hand would trigger the appearance of an AR interface to cycle through the different facade variations and controls. When the solar radiation heatmap was active, its legend was also displayed on their palm with the optimal lighting range for their location outlined. Figure 5 shows both *optimal* and *poor* solutions for both the office and conference room space with examples of the augmented direct solar and shadows in the space. Lighting visualizations are computed in real-time using *Unreal Engine* lighting, however the yearly solar radiation data is precomputed.

User interface (FRED). Figure 6 visualizes the AR design interface used to control the placement, selection, and simulation settings of the immersive and interactive workflow. The participant selects one of the four classes of facade choices to test ((1) *fins*, (2) *louvers*, (3) *kinetic*, or (4) *fritting*) and then can adjust a series of sub-(parameter)-components, such as their number and size. As the participant selects the facades in the interface, *FRED* instantly changes the overlaying facade designs on windows leveraging the linked BIM data. [*We plan to release FRED on GitHub with this paper to allow other researchers to use the AR design interface along with all study materials in a separate repository.*]

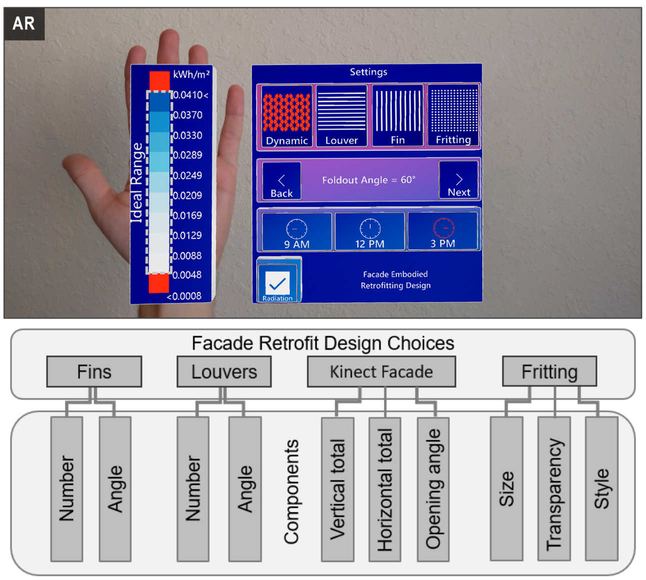

Figure 6: The AR Design interface used to control the placement, selection, and simulation settings. The user selects the facade choice to test, and then can adjust a series of parameter components and sub-component choices.

3.3 Methods

Study design. We utilized a between-subject design for our experiment to compare the two conditions (see Figure 4):

- **Conference Room:** Participants were situated in a conference room (14.64 ft x 23.23 ft) with windows on two walls (4 panels) and asked to optimize three variables (daylighting, view factors, and visual comfort). The wall sized windows are 10.01 ft x 8.70 ft and 12.70 ft x 8.70 ft.
- **Office:** Participants are situated in an office room with windows on one wall (2 panels) and asked to optimize three variables (daylighting, view factors, and visual comfort). The office room is a 12.17 ft x 9.76 ft room with a wall-sized window that is 12.46 ft x 8.42 ft.

For **view factors** participants are asked to minimize the percentage the facades occlude the outside environment views (100% full occlusion to 0% no occlusion). **Daylighting** is determined by the light cast in the space itself augmented by the AR. Each facade generates different daylighting and is most prevalent in the first light bounce and shadows. Usable *daylighting* ranges 100 to 5000 lux. **Visual comfort** identifies and minimizes areas below 100 lux (low light) and areas > 5000 lux (potential glare) using the daylighting energy visualization from the interface.

Procedure. The participants read the consent form and provided consent, were assigned their participant ID, randomly assigned a room condition, and we then collected their demographic data. They were then screened for any physical abnormalities and answered the survey material outlined in Section 3.1. Next, they watched a short video explaining facade designs, the task, multi-objective variables, and the user interface. Participants were then asked to review and think about the design choices and make a guess of which facade would solve the multi-objective optimization problem (without AR) and explain why they chose it. A short in-device training was completed to help familiarize the user interface. This training process consisted of participants selecting specific facade variations and time of days. After completion of training, the participants were instructed to browse different facades, move throughout the space, and judge visualizations. Finally, they were asked to pick the best solution as their last design. Post-task we first asked them to explain why they choose their last design.

Hypotheses. Our hypotheses focused on the effectiveness that AR has on participants evaluating optimal design solutions. Additionally, we investigated how they come to their choices by looking at the sequence and time spent navigating the solution space.

- **H1:** BIM-enabled AR (*FRED*) increases the optimal choice of facade design selected by the participant.
  - **H1a:** BIM-enabled AR (*FRED*) increases the optimal choice of view factors.
  - **H1b:** BIM-enabled AR (*FRED*) increases the optimal choice of daylighting.
  - **H1c:** BIM-enabled AR (*FRED*) increases the optimal choice of visual comfort.
- **H2:** High-performing participants who select more optimal designs spend more time on optimal solutions than low-performing participants.

3.4 Measures

We quantified the objective design scores and data, and collected subjective questionnaires and design evaluations to measure the effectiveness of AR in retrofitting. We analyzed the data between the office and conference room. We then post hoc analyzed how high and low performers examined the different designs to understand how this impacted their final choice.

Objective measures. For each participant session, we recorded every design viewed and the duration of time they spent investigating its impacts in the space. The facade designs and their BIM geometry were simulated in *Rhinoceros 3D* and connected to an annual daylight simulation engine *Ladybug* [51]. This tool uses energy and daylight simulation engines *EnergyPlus* ([11]) and *Radiance*

Facade Design	Opt	Rank	VF	VC	DL	PD
DYNAMIC_0	▲	5	16	1	9	0
DYNAMIC_30	▲	2	15	2	2	0
DYNAMIC_60	▲	3	10	7	6	0
DYNAMIC_90	■	10	4	12	12	0.009
FIN_10_30	▲	4	6	8	7	0
FIN_10_70	▲	1	11	3	1	0
FIN_20_30	■	9	8	9	8	0.007
FIN_20_70	■	14	13	4	3	0.028
LOUVER_10_30	■	12	5	11	11	0.016
LOUVER_10_70	■	11	12	5	4	0.015
LOUVER_20_30	■	15	9	13	13	0.034
LOUVER_20_70	■	8	14	6	5	0.005
FRITT_15_5	■	13	2	16	16	0.016
FRITT_15_10	▲	7	1	14	15	0
FRITT_30_5	■	16	7	15	14	0.048
FRITT_30_10	▲	6	3	10	10	0

Table 1: Data for the objective measure of optimal designs in the conference room. Opt is a binary value if its *optimal* ▲ or *poor* ■, Rank is the overall *rank score* of the 16 choices, VF is the *view factor* rank, VC is the *visual comfort* that show the brightness discomfort rank, DL is the *daylighting* rank, and PD is the *Pareto Frontier* distance.

([60]) to compute yearly energy and daylighting radiation analyses on a discretized 1 ft. x 1 ft. analysis plane. The Lux levels at each cell are scored if they are too low, usable, or too high. The designs are then rated based on their annual usable light levels (daylighting), and their visual comfort (amount of too low (eye strain) and too high (glare) levels). Section 2.3 explains how we then measure these multi-objective values to determine the optimal score based on the R^2 distance they have in the parameter space to the most optimal space in the graph. The overall rankings of these designs and their rankings for each individual factor are shown in Table 1. (Due to space constraints, only the rankings for the conference room condition are shown here.)

Subjective measures. We utilized questionnaires to determine the reasoning how and why participants came to their final facade choice. First, we asked an eight question instrument (Table 2) to understand their solution. The responses were recorded using a 7-point scale (1 = *Minimal effectiveness*, 7 = *Maximum effectiveness*).

4 RESULTS

We evaluate our data in three ways. First, we compare all participants across the two room conditions, to determine the overall effect of AR in assisting the discovery of more optimal solutions, and where participants spent their time during their decision-making processes (Section 4.1). Then we evaluate high and low performers to determine any difference in their decision-making processes. Lastly, we look at participants who displayed the most significant change *pre* and *post* design choice rankings to better understand how they explored the solution space. To measure differences between results, we utilized paired two-tailed t-tests with a significance level of 0.05. To measure differences between time spent

#	FRED Assessment Questionnaire items
Q1	Why did you choose your final facade design?
Q2	How much did the weight of the AR device affect you?
Q3	How accurate did the hand interaction with the interface components feel?
Q4	How much did the visualization of facade configurations help with the overall experience?
Q5	How easy was it to change the facade configuration from the user interface menu?
Q6	How accurately did you perceive the simulation of glare, lightning, and radiance in the room?
Q7	How easy was it to solve the study design task?
Q8	Is there anything you like/dislike from the experiment or suggest improving?

Table 2: Post Questionnaire issued to participants to gather subjective data of the BIM-AR experience.

looking at facades we utilized unpaired two-tailed t-tests with a significance level of 0.05. Prior to conducting all two-tailed t-tests, the normality of distribution of all compared data was confirmed using *Shapiro-Wilks* tests at the 0.05 significance level.

4.1 Overall Objective Measures

The analysis was performed on the dependent measures calculated per condition for the pre-experiment (i.e. blind selection) and post-experiment (i.e. AR-enabled selection) choices. The objective measure results of the overall optimal facade design selection are shown in Figure 7. This shows a box-and-whisker plot of the participants' *pre* and *post*-selection facade ranking showing the mean and the quartiles for the conference room (n=22) and the office (n=22). Lower numbers represent the more optimal facades, while higher numbers are less optimal designs. The violin plots display the distribution of the participants' chosen facade designs. This shows a positive shift from using AR in the mean score.

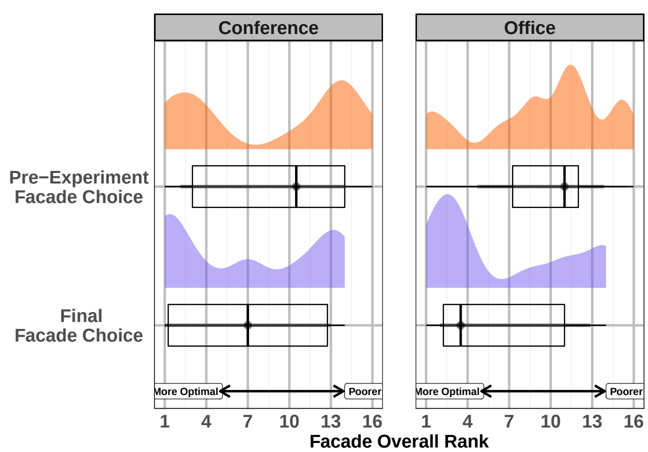

Figure 7: Display of the distribution and box-and-whisker plots of the mean ranked scores of participants under each condition for the *pre* and *post* facade rankings.

Overall Performance Data

Measure	M	Mdn	SD	*t*	*df*	*p*
All (Pre)	9.0	11.0	5.194	2.297	43	0.027
All (Post)	6.614	4.0	5.122			
Conf. (Pre)	8.5	10.5	5.821	0.964	21	0.346
Conf. (Post)	6.909	7.0	5.327			
Office (Pre)	9.5	11.0	4.564	2.485	21	0.021
Office (Post)	6.318	3.5	5.02			

Table 3: Summary table of the main results measured.

Table 3 is a summary of the main results displaying data of the *t*-test to determine whether the *Means* of the *pre* and *post* groups changed. For both individual conditions and the entire participant pool, there was a decrease in *Mean* facade rank, which demonstrates participants selected more optimal facades after using the spatial AR interface. A paired sample *t*-test verified that this difference was significant, $t(43) = 2.297$, $p = .027$, for the entire study pool *pre* ($M = 9$, $SD = 5.194$) and *post* ($M = 6.614$, $SD = 5.122$) experiment. For participants assigned to the conference room condition, although the quality of *Mean* facade selection did increase, the difference between pre ($M = 8.5$, $SD = 5.821$) and post ($M = 6.909$, $SD = 5.327$) was not as significant, $t(21) = 0.964$, $p = .346$. For participants assigned to the office condition, the difference between pre ($M = 9.5$, $SD = 4.564$) and post ($M = 6.318$, $SD = 5.02$) was significant, $t(21) = 2.485$, $p = .021$.

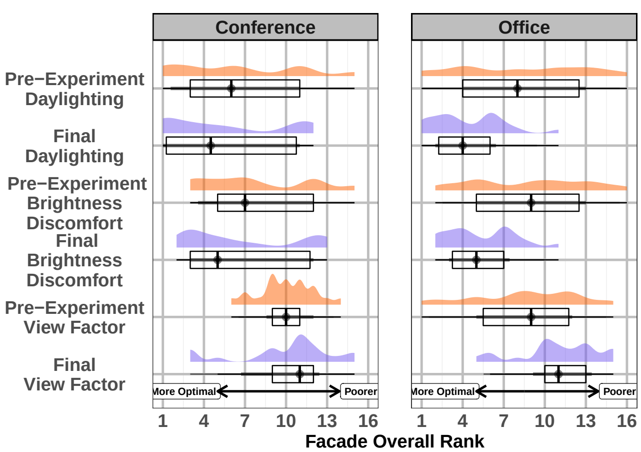

Figure 8: The distribution and box-and-whisker plots of the mean ranked scores of participants for the *pre* and *post* facade rankings to examine change in each multi-objective variable.

We also examined each individual variable (daylighting, visual brightness discomfort, and view factors) shown in Figure 8. This shows a box-and-whisker plot of the participants' *pre* and *post*-selection facade ranking showing the mean and the quartiles. Lower numbers again represent more optimal facade designs, higher numbers are less optimal. The violin plots display the variable distributions. This indicates more change in *daylighting* variable than *visual discomfort* or *view factors*.

Influence of Variables on Performance Data

Measure	M	Mdn	SD	*t*	*df*	*p*
All(DL) (Pre)	7.386	6.5	4.657	2.564	43	0.014
All(DL) (Post)	5.0	4.0	3.589			
All(BD) (Pre)	8.341	7.5	4.063	2.64	43	0.011
All(BD) (Post)	6.045	5.0	3.471			
All(VF) (Pre)	9.273	9.5	3.098	-1.73	43	0.091
All(VF) (Post)	10.477	11.0	3.274			
Conf.(DL) (Pre)	6.5	6.0	4.543	0.66	21	0.516
Conf.(DL) (Post)	5.591	4.5	4.339			
Conf.(BD) (Pre)	7.818	7.0	3.96	0.818	21	0.422
Conf.(BD) (Post)	6.727	5.0	4.177			
Conf.(VF) (Pre)	10.0	10.0	2.0	0.113	21	0.911
Conf.(VF) (Post)	9.909	11.0	3.598			
Office(DL) (Pre)	8.273	8.0	4.702	3.22	21	0.004
Office(DL) (Post)	4.409	4.0	2.612			
Office(BD) (Pre)	8.864	9.0	4.19	3.239	21	0.004
Office(BD) (Post)	5.364	5.0	2.498			
Office(VF) (Pre)	8.545	9.0	3.814	-2.305	21	0.031
Office(VF) (Post)	11.045	11.0	2.886			

Table 4: Summary table of the individual variable effects measured.

Table 4 presents data of each individual variable's effects. This shows a *t*-test to determine whether the *Mean* of the *pre* and *post* groups demonstrate change between selected facade rankings on daylighting, visual brightness discomfort, and view factor scales. Overall, many of the factors tested show significant differences in *pre* and *post* experiment ranks. When grouping all participants together, the daylighting and visual brightness discomfort rankings decreased (i.e. more optimal) and this difference was significant. The view factor ranking increased (i.e. less optimal), but this difference was not significant. Those assigned to the conference room condition demonstrated more optimal choices for all three factors in their final selection, although these differences were not significant. For participants assigned to the office condition, all variables saw a significant change. Daylighting and visual brightness discomfort rankings of the final selection were more optimal, however the view factor ranking was less optimal.

To better understand the decision-making of the participants, we investigated the time spent exploring the solution space. Time was only counted if participants viewed a facade for a minimum of two seconds. This ensures time spent cycling through the different options looking for a specific solution is not counted. The participants spent 49.43% of time on optimal solutions as they explored the different facade choices. Participants spent the most time examining the *Louver* facade with many small strips (12*th* ranked solution), while they only spent 8.68% of time in the top-ranked solution.

4.2 Comparing High and Low Performers

To get a deeper understanding decision-making processes, we split the participants post hoc into high performers (n = 22) and low performers (n = 22) based on a median split of their final facade

Time Spent on Different Facades (Seconds)

Measure	M	Mdn	SD	t	df	p
High (Optimal)	499.60	475.69	286.16	0.655	30	0.518
High (Poor)	441.04	384.33	241.72			
Low (Optimal)	574.08	577.18	178.15	-1.419	30	0.166
Low (Poor)	682.77	661.14	249.40			

Table 5: Summary table of the high and low performers time spent on optimal and poor facades.

solution ranking. We investigated the time these groups spent exploring the overall solution space to see if they differed. The high performers spent 53.11% of their time on optimal solutions when exploring the different facade choices, while the low performers spent 45.68% of their time in optimal solutions. The high performers spent the most time looking at the *4th*, *12th*, and *3rd* ranked facades, while the low performers spent their most time looking at the *12th*, *15th*, and *16th* ranked designs (see Table 1). Table 5 presents a summary of the t-test results used to determine whether the *Mean* time spent looking at optimal and poor facades differed for the high and low performers. High performers saw a greater *Mean* time spent viewing optimal facades (M = 499.60 s, SD = 475.69 s) over poor facades (M = 441.04 s, SD = 241.72 s), however this difference was not significant, $t(30) = 0.655$, $p = 0.518$). Lower performer spent less *Mean* time with optimal facades (M = 574.08, SD = 178.15) than poor facades (M = 682.77, SD = 249.40), but this difference was also not significant, $t(30) = -1.419$, $p = 0.166$).

4.3 Subjective Measures

Participants answered the questions in Table 2 post-experiment questionnaire by rating their responses on a using a 7-point scale (1 = Minimal effectiveness, 7 = Maximum effectiveness). The responses were as follows: Q2 (M = 1.942, SD = 1.461), Q3 (M = 4.105, SD = 1.460), Q4 (M = 6.048, SD = 1.273), Q5 (M = 5.097, SD = 1.586), Q6 (M = 5.419, SD = 1.409), Q7 (M = 5.000, SD = 1.449).

5 DISCUSSION

In this section, we discuss the implications of our main findings that BIM-enabled AR is effective at improving the selection of facade design choices and its influence on decision-making in multi-objective optimization problems in the built environment.

BIM-enabled AR is effective at improving facade design choices [RQ1]. Our objective was to understand the effects of AR in retrofitting facades by enabling participants' to explore optimal facade designs. Our first set of hypotheses (**[H1]**) stated they would improve their selection to more optimal facades. Examining the data shows that this held true for the participant pool as a whole and participants assigned to the standard office, but not for the more complex conference room. For the office, the results of the two tailed t-test indicated a significant positive effect in facade selection concluding use of *FRED*. For the conference room, facade rankings again improved, however the difference was not deemed significant according to our two tailed t-test. This, along with optimal mean scores for Q2, Q4, and Q6 (see Table 2), demonstrates potential for AR to be an effective retrofitting tool for stakeholders who do not have expertise in architectural design, however further study is needed as the room becomes more complex.

Our sub-hypotheses (**[H1a]**, **[H1b]**, **[H1c]**) stated the individual factors rankings of post *FRED*-use facade selection would increase. For the office, all three factors saw a significant change, however the view factor of the final facade selection increased in *Mean* rank, meaning it was less optimal. This could be due to a reliance on the toggle-able solar radiation heatmap participants had access to. Participants may have felt overwhelmed by an unfamiliar subject matter and gravitated towards quantitative measures over more subjective aesthetic factors. This line of thinking is supported by various participant comments and a high mean score of Q7 (Table 2), and future research with industry professionals will likely provide more clarity. For the conference room, all factors improved in *Mean* ranking, however none of these improvements were deemed significant by the two tailed t-tests. In addition to increased complexity, the conference room also was much larger and open than the office room. The lack of effectiveness can also be attributed to the *HoloLens 2*'s limited field-of-view (FoV) vs. normal human perception inducing unnecessary head movement vs. the office space.

Decision-making in multi-objective optimization [RQ2]. Our second objective was to better understand the decision-making processes when facing multi-objective optimization problems in practice. This is compounded when there are non-linear tradeoffs between the objectives increasing the complexity of the problem. Often the solution space is difficult to understand and compare with traditional methods. AR provides a better ability to spatially understand the solution space. Our second hypothesis (**[H2]**) looks at where the participants are spending their time as they explore the solution space. Intuitively, we expected the higher performers to gravitate to better designs, and lower performers to be stuck in local minimums of the solution space. There was little change in how the performers spent their time, but it was not as suggestive as expected. High performers spent more time viewing optimal facades and low performers spent more time viewing poor facades, however these were not able to be deemed significant by the unpaired t-tests. One possible explanation for this is participants may have had trouble remembering which facades they considered more optimal during the experiment.

Implications and Future Work. While this work is designed to evaluate just retrofit facade design, its implications extends to other BIM-enabled AR retrofitting design contexts as well. Analyzing how participants interact with embedded BIM-driven simulation data in situ using AR provides guidance for developing more efficient BIM-enabled AR retrofitting systems. While it was expected that in situ visualizations would increase participants' prioritization towards designs excelling in aesthetic view factor, it was shown the exact opposite occurred and that the system encourage greater understanding and usage of the embedded simulation lighting data. Future AR systems aimed at improving the built environment should continue to embedded simulation data in the environment and explore alternate visualization techniques for this data. In larger environments, techniques to mitigate the field-of-view limitations of current AR hardware should be explored as well, as we believe this is a contributing factor to a lack of significant improvement in our larger conference room testing environment. In situ access to other BIM-driven simulation data visualization methods, such as handheld manipulable room models, may be of interest for this issue.

Limitations. The current study has COVID-19 participant limitations and we believe future research will benefit from continued human-subject testing against additional conditions, such as choosing designs on a desktop computer. The user interface and visualization representation can also be manipulated in experiments to ensure designs and options are clear and mimic current design methodology and principles. We could also explore additional facade designs and give future users the ability to sketch their own solution. It is likely this capability will provide a testbed to study creative solutions to freely explore this multi-objective space.

6 CONCLUSION

In this paper, we presented a human-subject study where we examined the effectiveness of AR facade retrofitting to better understand decision-making efficiency allowing participants to discriminate optimal and non-optimal facade choices. Our results indicate that BIM driven AR can positively affect participants selecting more optimal designs. Additionally, this approach provides better subjective understanding of the space and interactions of complex variables. There is a clear benefit to spatial visualizations in the early-phase retrofitting process. The ability to leverage BIM-enabled AR could aid in retrofitting and provide a basis for deeper research on its impact on improving solutions and problem-solving.

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