Embodied Facade Retrofit Design With Augmented Reality in the Built Environment

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Abstract

This paper presents a framework for collaboratively evaluating facade retrofit designs in-situ using Augmented Reality (AR). *Building Information Modeling* (BIM) tools have been seeing increased use, driving the collection of detailed information throughout a building's life cycle. AR combines the visible real-world with superimposed computer-generated information, for example, permitting users to visualize proposed changes and simulation data while on-site. Our approach combines these disruptive technologies into a design tool for early-phase facade retrofits through to the final design. This method enables us to address a range of design and retrofit scenarios improving daylighting, energy efficiency, and aesthetics of a structure while maintaining a building's function and comfort. Our system will enable architects, engineers, and facility stakeholders to explore viable design options that satisfy construction and retrofitting project goals. Our framework is applied to a demonstration office and conference room retrofit project illustrating the potential for interactive in-situ redesign evaluation

Key Innovations

- AR interface for in-situ facade design.
- AR-BIM immersive review of building daylighting and radiation performance aims.

Practical Implications

This paper presents a holistic decision support framework for retrofit facade prototyping that allows architects, engineers, and facility stakeholders to understand both their design and its daylighting performance implications.

Introduction

Facades play a significant role in both a building's character, occupant well-being, and a building's overall energy performance. Designing effective facades is challenging because the process consists of a multi-objective optimization problem that often requires trade-offs between conflicting goals. Additionally, facades act as protective filters for the weather, noise, and environment, and perform as regulators between outdoor and indoor conditions. They are often designed to optimize for protection and regulation providing maximum comfort to occupants as well as increasing a building's daylighting and energy performance. When designing facades architects attempt to additionally optimize occupant well-being by addressing daylight, glare, view indexes, aesthetics, thermal comfort, and structural performance. Retrofits, renovations, and refurbishments often provide an opportunity to update the look, as well as improve these functional indicators.

Frequently architects and engineers face considerable uncertainty about how their design decisions impact the overall holistic building performance. A design choice may positively affect performance in one fashion while negatively affecting other criteria. Moreover, it is important to understand the connection between the built space energy demand and its occupant who inhabits them. With the more stringent advanced daylighting and energy objectives, the architecture, engineering, and construction (AEC) industry finds there are few tools and processes to properly conduct advanced energy retrofits in the built environment that promotes a human-centric design. There are recent tools that help with daylighting previsualization (Rockcastle et al., 2018) and AR / VR experiences (Nasman and Cutler, 2013). Therefore, it is essential that collaborative in-situ tools for architects, engineers, and facility stakeholders are available to design facades and understand their performance impacts of daylight entrance, energy use, and occupant satisfaction.

In this work, we present a novel framework *FRED* (Facade Retrofitting Embodied Design) that allows architects, engineers, and facility stakeholders to design facades immersively in-situ while providing a supportive methodology based on interactive visualizations and feedback on daylighting and energy performance. Architectural renders typically are seen in post-design and do not provide opportunities to significantly alter the fundamental form and shape of the facade. What is unique about our framework, *FRED*, is that it links *Building Information Modeling* (BIM)

Figure 1: A demonstration of our AR-BIM framework that allows designers to collaboratively design facades by changing design parameters in-situ for retrofits and see the impacts on daylighting. (The white facade shown is generated by our system.)

and Augmented Reality (AR) to provide an embodied and enactive experience that couples the design with the results in a space permitting the observation of daylight and energy performance of the early-phase retrofitting design process.

Building Energy Modeling (BEM) is often conducted during later design stages by complex software, but integrating such advanced calculations into early-phase retrofitting planning can provide opportunities for changes and greater innovation. When the designer is surrounded by the retrofit design in the structure using AR, they are able to rapidly iterate and understand the impact of the alterations within a space. Additionally, architects and engineers might collaborate on a facade design adjusting parameters and visualizing the BEM results (Figure1).

Background

Facade Designs

Facade design strategies are solar shading systems that can protect buildings from solar radiation, glare, and heat gain. These objectives can be achieved by building elements such as louvers, brise soleils, awnings, overhangs, fins, fritting, and tinting. Figure 2 shows four different facade types on structures, and it shows their construction drawings. Such elements are difficult to simulate due to their increasing geometric complexity. Exterior shading elements are often paired with high-performance glazing, while blocking the sun, they can simultaneously obstruct view factors. While movable fenestration systems adjust to outdoor conditions, they are often noisy and distracting to occupants. Architects need to be cognizant of the impact their choices will have when contending with multi-objective optimizations (Grunske, 2006). *FRED* provides a way for architects to test if kinetic facades could be distracting by visualizing changes in direct solar daylighting patterns. The optimal facade design will consider initial capital and operational costs, yearly energy, comfort, and daylighting performance factors (Chantrelle et al., 2011).

Traditionally, all building elements and details are designed separately. Architects leverage parametric modeling to optimize facades by automatically changing a range of parameters such as the rotation, amount, and location of fenestration elements, while potential designs can be evaluated for comfort, radiation, and energy studies (Eltaweel and Yuehong, 2017). Parametric design tools and methods provide a framework to create a number of optimal designs in a shorter period of time informing the process. Parametric modeling can also lead to ambiguity when analyzing vast amounts of data for multi-objective problem spaces, frequently neglecting occupant needs Montoya-Olsson (2020). It is difficult to visualize a large set of design parameters and truly understand their effect on a space.

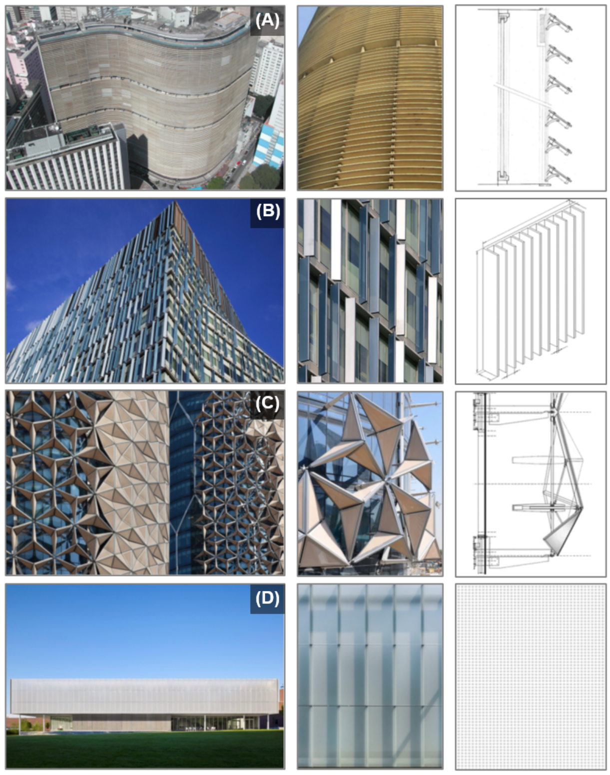


Figure 2: Illustration of several currently used shading facade designs across the world: (A) Edifício Copan Building, featuring concrete horizontal louvers (Oscar Niemeyer); (B) Blue Fin Building, featuring vertical fins (Allies and Morrison); (C) Al Bahr Towers, featuring a kinetic shading system (AHR); and (D) JCCC Fine Arts and Design Studio, featuring Lumi Frit glass (BNIM).

BIM-based Retrofitting Design

When planning retrofits, renovations, and refurbishments for existing buildings architects can face a wide range of challenges such as the complexity of the building's current functionality or the presence of occupants during the retrofit process. BIM represents a set of digital processes and representations that documents datastreams throughout a structure's life cycle providing building blocks to inform retrofitters (Sanhudo et al., 2018). Typically, BIM data contains a 3-dimensional geometric model that can be leveraged to design facade elements and utilized for analysis and simulation of energy, daylighting, and comfort. These 3D models provide both physical and functional characteristics of design elements as well as a correlation amongst components. So as elements are created and tested, the changes are reflected in the underlying BIM data associated with the site for BEM.

AR as an Embodied Modeling and Design Tool

Augmented Reality (Sutherland, 1965) provides architects and engineers in-situ evaluation tools to support design decisions by overlaying information on a user's surroundings (Dunston and Wang, 2005). This provides context for understanding how a design will integrate and relate to a space avoiding construction issues. Significant data can be visualized in the augmented overlay providing better tools to utilize during an on-site retrofit design walk-through (Kim et al., 2013). Recent advancements in AR and VR advanced research in creating and visualizing designs in 3-dimensional contexts, over 2-dimensional screens. Recent research has developed AR interfaces for the AEC industries to support all phases from an architectural concept through design (Whyte, 2002), to construction (Mitterberger et al., 2020), and building maintenance (Henderson and Feiner, 2010). AR provides an opportunity for BIM data to be directly integrated into in-situ visualizations permitting collaborative inputs from practitioners and clients (Koutsabasis et al., 2012). These 3D graphical augmentations enhance the traditional design process. Peng et al. (2018) allowed users to freely manipulate 3D geometry in AR, while others have developed a system to sketch 3D designs directly attached to existing physical objects (Li et al., 2019).

Augmented Reality interactions and visualizations couple the designer and their environment. This embodied approach proposes that to truly understand a design and its implications it must be understood within context providing mechanisms for interactions and exploration (Gibson, 1979). Clark and Chalmers (1998) proposed that kinesthetic sensorimotor body interaction was fundamental to cognition. Mallgrave (2013) argued how our embodied condition of immersion underpins the aesthetics, culture, emotion, and experience of architecture. Robinson and Pallasmaa (2015) discussed how architecture and design link the mind and body. Jäger et al. (2016) proposed embodied interactions when designing adaptive architecture.

FRED relies upon "4E" cognition (embodied, embedded, enactive, and extended) theoretical foundation (Newen et al., 2018) for retrofitting facades onto a building. The subject engages both their body and brain to create facades (*embodied*). Creating designs in-situ enables an individual to visualize both the design and its daylighting implications in the space itself (*embedded*). Architects can store and save ideas to envision different facades and in a space testing different design concepts (*extended*). Lastly, designers can freely move through the space to understand the 3-dimensional interaction of light, comfort, and energy usage in the design shapes (*enactive*). This *4E embodied design* approach provides opportunities to engage the body in the retrofitting design process.

Methodology

The main goal when developing *FRED* was to provide the architects, engineers, and facility stakeholders with the ability to design and view facades while in-situ within a structure keeping the environment closely connected. FRED permits the architect to work in the building, and that is augmented so they can see the design's geometry and its daylighting impact. FRED is a 3D model-based design process that gives architects and engineers insight to efficiently design and simulate facade modifications. By leveraging BIM data of the environment and providing an interactive design experience, designers can focus on selecting the optimal facades for a space. Having BIM data available while within the space enables FRED users to identify ideal locations for facade additions during retrofits. We present the architecture of the *FRED* system in Figure 3.

BIM data allows *FRED* to identify areas to add retrofitting modifications. *FRED* highlights areas such as walls and windows where facade modifications are envisioned, while BIM provides the context of the building's structure. The feasibility, functionality, and aesthetics are presented in an immersive fashion via AR enabling architects to move around a space and evaluate options. *FRED* empowers designers to take proposed facade modifications to permit them to perform daylighting simulations and visualize the results in AR.

Wearable AR hardware enables an immersive hands-free interactive and design workflow. Such modeling systems provide an embodied and enactive experience with feedback within a structure's context during the design process. The *FRED* system uses an AR head-mounted display (e.g. Microsoft's *HoloLens 2*) that an architect wears inside the space they are retrofitting with a facade change. The commoditization and democratization of AR hardware have popularized 3D design drawing and modeling tools. The *FRED* system architecture presented in Figure 3 has three modules: (1) BIM Data module, which processes the 3D-dimension geometry and material properties, (2) AR module, which captures movement and input, and visualizes the facade geometry and daylighting simulation, and (3) 3D-modeling module, which coordinates the geometry process and daylighting simulations. When the user completes the facade modification, *FRED* transfers those changes to the BIM module to store.

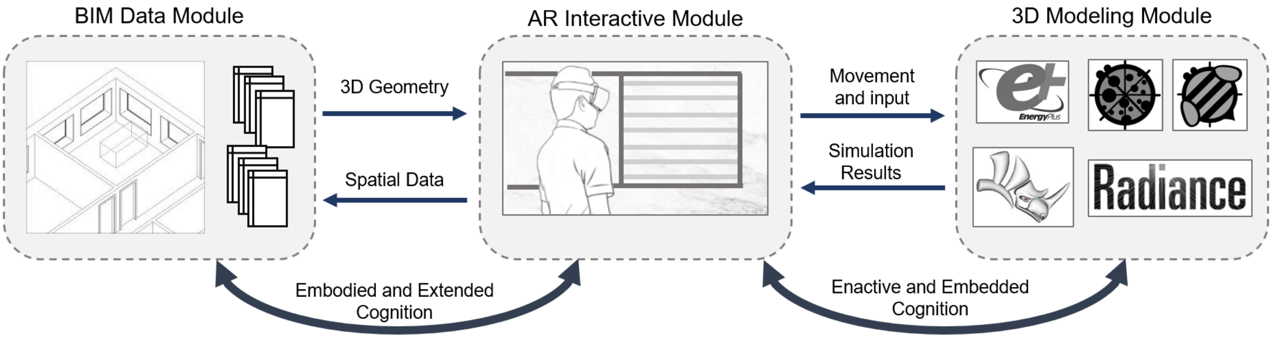


Figure 3: FRED software framework modules: (1) BIM data sub-module; (2) AR interactive sub-module; and (3) 3D modeling sub-module. This framework enables embodied, extended, enactive, and embedded design workflows.

BIM Data Sub-module

The *FRED* BIM module is used to import 3-dimensional geometric models, Which can consist of digitized CAD geometry or detailed laser scans of the environment. This data also provides object properties such as colors, materials, finishes, and additional technical information, and is linked to the AR and 3D design module. The BIM data contains information that enables the alignment of the building structure to the geometric model throughout the design process and permits the AR module to align the model with the structure (Rahimian et al., 2014). Finally, the BIM module processes the modifications and transfers them from the 3D modeling module to the BIM.

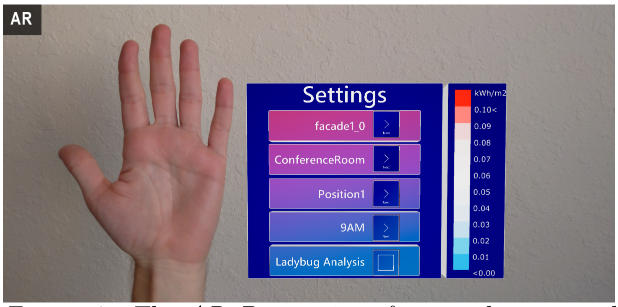


Figure 4: The AR Design interface used to control the placement, selection, and simulation settings of the immersive and interactive design workflow.

AR Interactive Facade Design Sub-module

The AR module utilizes Epic's *Unreal Engine* for data and information display, and interfaces with the Microsoft *Hololens 2* AR hardware to track movement and visualize information to the designer. An interactive user-interface controls the parametric design parameters for the facades. *HoloLens 2* tracks a user within the environment by matching the features of the space to the BIM data. This attribute of *HoloLens* attaches the interface to the user's left hand and is visible only when their palm is facing up (Figure 4). The module's interface permits the designer to select from a series of facade choices, with the controls and interface appearance designed in accordance with AR-interface recommendations standards. *FRED*'s AR editor supports overlaying various facade designs on windows or the structure leveraging the linked BIM data.

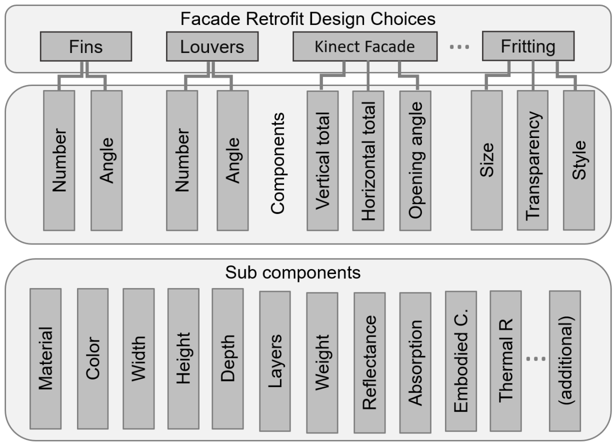


Figure 5: The retrofit design choices of FRED. The designer selects the facade choice to test, and then can adjust a series of parameter components. Then the designer has a series of sub-component choices to adjust to finish the design.

3D Modeling and Simulation Module

FRED's 3D Modeling and Simulation Module provides the ability to create and position geometry, and it simulates and visualizes daylighting and radiation simulations. To fulfill designer requirements of selecting from a variety of facades for retrofitting, *FRED* implements four choices in the test system: fins, louvers, a kinetic facade design, and fritting, see Table 1.

Even though it is a prototype system, *FRED* can be easily extended to accept additional facade choices, with each selection having a number of components. Architects can incorporate modifiable parameters to control placement and parameters of facade geometry in real time such as the number of fins or louvers, the angle the components are placed, or the size and spacing. Designers are provided additional choices including the ability to adjust the sub-component parameters, for example, the color, material, reflectance, and embodied carbon. This provides a series of extended

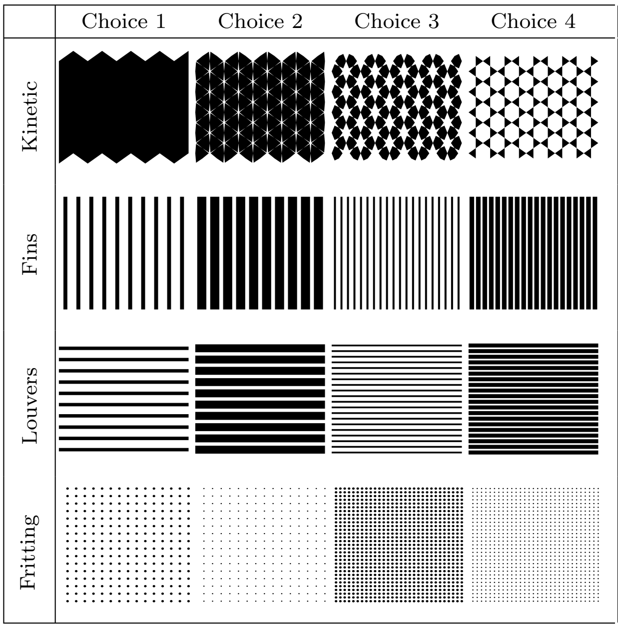


Table 1: The test facades with each row corresponding to a different facade style. From top to bottom: kinetic, fin, louver, and glass fritting.

design tools to allow the designer to embed their design in-situ. Figure 5 provides a visualization of interface design choices, components, and sub-component parameters. The facade models are then incorporated into the real-world test environments, and positioned according to the desired window or structure.

The 3D modeling and simulation module also performs a variety of daylighting and radiation analyses based upon design selections. Recent advances have speedup climated-based daylighting modeling by leveraging the GPU (Jones and Reinhart, 2017). These simulation results can then be visualized in the designer's AR headset. This assists them in determining design implications upon the space. Furthermore, the 3D modeling and simulation module simulates the solar pattern of direct lighting within the space. Figure 6(Left) depicts an example of a kinetic facade placed in the BIM environment, where virtual geometry of the facade occludes a virtual sun. *FRED* provides solar controls to allow the designer to alter the display's effects for different times of day and solar angles. This simulation and visualization feature enables the exploration of glare, luminance, and daylighting impacts of various facade choices. Direct solar daylighting is implemented by the raytracing module in Epic's Unreal engine to provide accurate direct solar illumination into the space.

Additionally, the new facade designs and their geometry can be transferred back into Rhinoceros 3D, and connected daylight simulation engines (e.g. *Ladybug*, *Honeybee* or *ClimateStudio*). The energy and daylight simulation tools use *EnergyPlus* (Crawley et al. (2001)) and *Radiance* (Ward (1994)) to compute complex energy and radiation analyses. These results can be viewed interactively in augmented reality as a result of the link between BIM and AR modules in *FRED*. Figure 6(Right) shows an example radiation analysis simulation and visualization for a test structure and facade. (*Note: the color scheme of the radiation analysis can be modified by the interface, blue was selected for this paper as it provided an effective contrast in the test space.*)

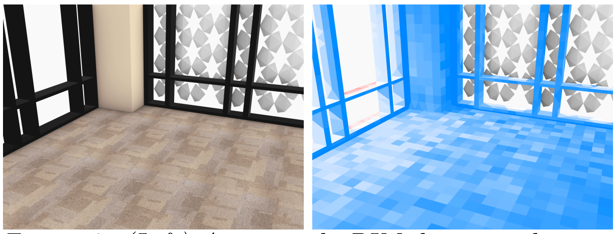


Figure 6: (Left) An example BIM data visualization of our test building environment with a facade design in place. (Right) An example daylighting radiation analysis applied. The BIM data is matched in reality to visualize the designs and daylighting in AR.

Results

This section presents the implementation of the proposed *FRED* system. We selected two different spaces located in the South-Eastern United States, as study objects since these buildings suffer from daylighting and thermal issues in the sub-tropical climate. Each space has different retrofitting challenges. We simulate the direct daylighting hourly from 9:00 am to 5:00 pm. to demonstrate *FRED*. The radiation analyses use *Radiance* and *Climate Studio*.

Using FRED for Daylighting Simulations

Using *FRED* (Table 2) is intuitive with little training, and permits quick adjustments in real-time. First, the room needs to be registered and aligned within the AR system to enable reliable and accurate alignment with the underlying BIM data and simulation results. This system permits manipulation of daylighting simulation settings utilizing a menu triggered by way of a hand gesture, allowing the display of facade alteration. The AR daylighting is computed in real-time utilizing the Unreal Engine global illumination pipeline. The time required to compute each facade-position for radiation analysis along with data importation ranged from 30 seconds to one minute, with all calculations being performed on a host computer and streamed to the *Hololens 2* by wifi.

Parametric Retrofit Design Results

Daylighting and radiation analysis differences for the test facades vary significantly. Two of the tested facades (fins and louvers) cast a striped pattern shadow, with a similar visual effect in the radiation mapping except with interspersed colors. An alternative is a so-called "kinetic" facade since it moves altering the pattern based upon the time of day and season. The radiation map for a kinetic system permits isolated lighter blocks aligning with the openings between the triangles, which has a lower level of heating. Low density fritted facades had less of a noticeable impact on daylighting and radiational heating, but as the simulated density and element diameter increased, daylight and heat were reduced. *FRED* permitted the system operator to change between various facades and fritting with no real-time system issues. This could allow a designer to easily compare a variety of facades.

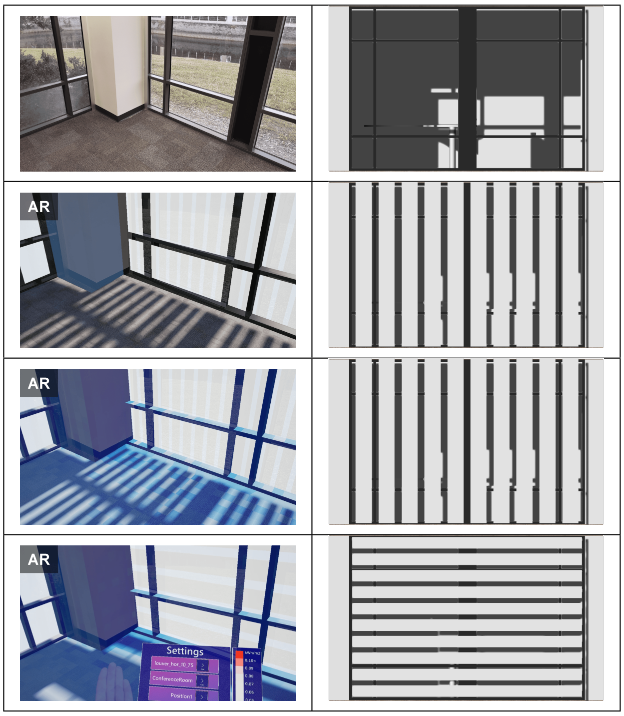


Table 2: The FRED usage process. Initially, no geometry is rendered, but after aligning and registering the room, the designer is able to change simulation settings using the AR menu.

Table 3 shows output examples from design choice alternatives, the 3D model of the retrofit design, and daylighting and the radiation analysis from the *FRED* AR system display. Several attributes can be altered in real-time including the facade type (e.g. louvers, etc.), time of day, and position of louvers which noticeably affects both the daylighting and radiation analysis mapping.

Figure 7 show objective data of the ideal facade variations *FRED* would guide users toward as they explore the design space. These variations attempt to balance excessive brightness and the view factor allowed. The brightness discomfort value, calculated with a facade applied to the window, is the percentage of room flooring that receives illumination from the sun in excess of the typical office lighting range of 100 to 5000 lux. An ideal value would be zero, indicating no excessive glare exists, causing inhabitant visual discomfort. View factor represents the percentage of outside view allowed by the facade and is solely an aesthetic factor, with a greater value mean-

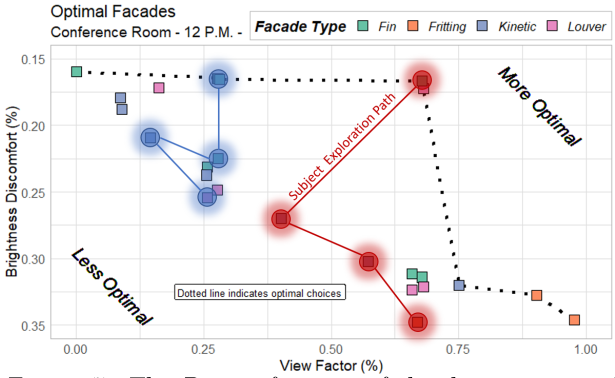


Figure 7: The Pareto frontier of the design space of two competing variables: discomfort and view factors. The red and blue paths show how subjects explore in AR to understand the space.

ing more outside visibility. *FRED* gives users the ability to analyze view factor by visualizing various facades on the window and enables a designer the ability to discern visual discomfort by highlighting areas that have the excessive solar impact using a radiation map. Given *FRED*'s embodied perspective, the system permits users reach these determinations faster than traditional facade design methods.

Discussion

Given the increased need for retrofitting structures, there is a need for tools to help save and preserve buildings and structures. New facades are one approach to modernize the appearance while improving energy performance. Because demolition and replacement with new structures amounts to nearly one billion square feet of occupiable space in the United States (Frey et al., 2011), this creates significant waste with the corresponding environmental impacts such as the failure to re-purpose or recycle materials that will accumulate in landfills. The *FRED* framework provides insights into retrofitting strategies, and supplies key performance indicators and impact metrics which fosters better design decisions.

As a building's function changes, its retrofitted form must be adapted. *FRED* permits embodiment by active body engagement and enactive visualization during retrofits. This coupling of body action and perception shapes the cognitive design as a whole. *FRED* enables subjects to relate the form and function by embedding the creative aspect by coupling environments and the occupants that inhabit them. Understanding a design's impact often necessitates movement and action in the space, this is based on the enactive thesis. Research has studied how *4E* approaches assist the creative process (Malinin, 2019). *FRED* integrates this theoretical foundation into an operational head mounted AR system. Adaptive retrofitting also provides greater benefits than traditional historic preservation because a structure is transformed to meet the needs of contemporary users (Plevoets and Van Cleempoel, 2013). FRED allows

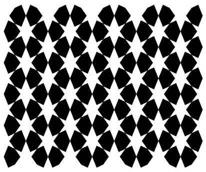
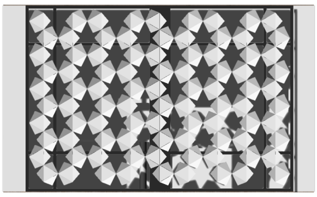
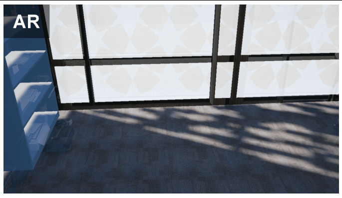
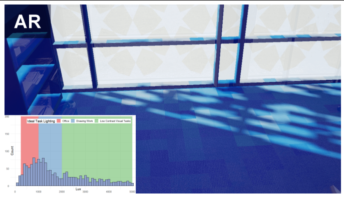
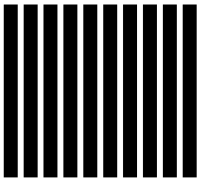
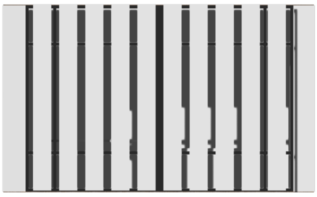
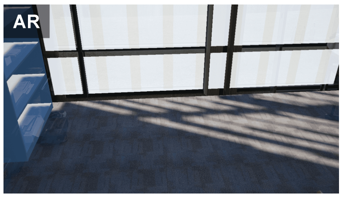
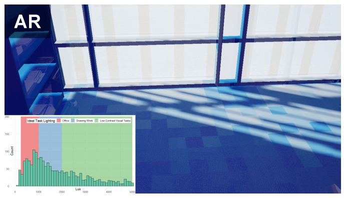
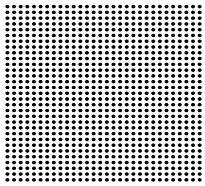
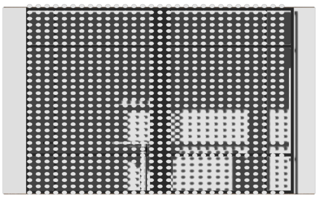
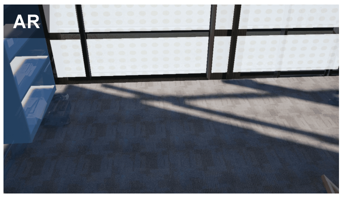
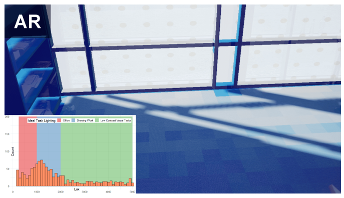
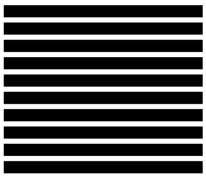
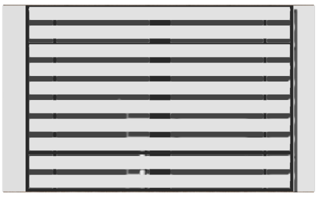
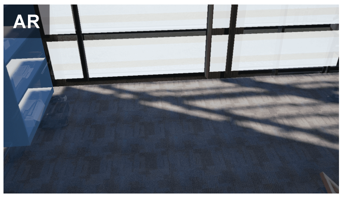
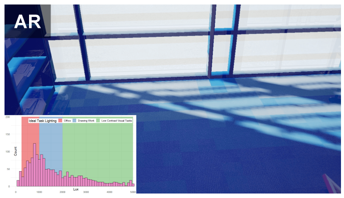
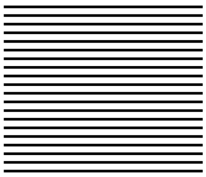
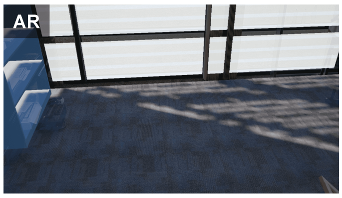
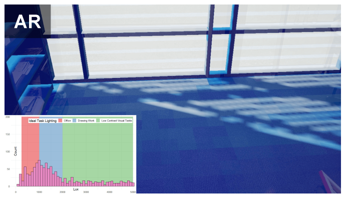
	Facade Design	3D Model	AR Daylighting	AR Radiation
Kinetic				
Fins				
Fritting				
Louvers (1)				
Louvers (2)				
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Table 3: Results from AR design variations of an office space. The designer is picks designs, which creates new 3D models, which are placed in the space simulating the daylighting, and solar radiation through AR.

for spatial exploration, and this context is essential for preservation goals.

Conclusion

The *FRED* framework presented in this paper demonstrates the potential of integrating BIM into a head mounted AR device to assist the design process for architects, engineers, and facility stakeholders. One benefit of *FRED* is the ability to compare retrofitting strategies on-site, which provides understanding of the affect design choices impart upon a space. While spatial data enables intuitive design, seeing the potential retrofit changes augmented in-situ provides improved comprehension of their form and function. The links between *FRED*'s modules further permit a designer to conduct daylighting and radiation simulations on-site. This is due to the system's capability to allow an architect to walk around a space and observe the true daylighting and heat radiation with a head mounted AR device. We implemented four facade strategies, which were tested in conference room and office settings to evaluate the *FRED* framework in real-world environments. Our future plans include extending facade design choices through Rhinoceros 3D (Rhino). Rhino is a popular computer design program amongst architects due to its ability to fit within the workflow and offer a variety of parametric facade designs based on the *Grasshopper* plugin. Additionally, we intend to run human subject studies to test how designers solve various retrofitting challenges. Our study will compare how 3D AR-BIM compares to 2D desktop workflows.

References

Chantrelle, F. P., H. Lahmidi, W. Keilholz, M. El Mankibi, and P. Michel (2011). Development of a multicriteria tool for optimizing the renovation of buildings. *Applied Energy 88*(4), 1386–1394.

Clark, A. and D. Chalmers (1998). The extended mind. *Analysis 58*(1), 7–19.

Crawley, D. B., L. K. Lawrie, F. C. Winkelmann, W. F. Buhl, Y. J. Huang, C. O. Pedersen, R. K.

Strand, R. J. Liesen, D. E. Fisher, M. J. Witte, et al. (2001). Energyplus: creating a new-generation building energy simulation program. *Energy and buildings 33*(4), 319–331.

Dunston, P. S. and X. Wang (2005). Mixed reality-based visualization interfaces for architecture, engineering, and construction industry. *Construction engineering and management 131*(12), 1301–1309.

Eltaweel, A. and S. Yuehong (2017). Parametric design and daylighting: A literature review. *Renewable and Sustainable Energy Reviews 73*, 1086–1103.

Frey, P., L. Dunn, R. Cochran, K. Spataro, J. McLennan, R. DiNola, and B. Heider (2011). The greenest building: Quantifying the environmental value of building reuse. *Preservation Green Lab, National Trust for Historic Preservation*.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Houghton Mifflin.

Grunske, L. (2006). Identifying" good" architectural design alternatives with multi-objective optimization strategies. In *Proceedings of the International conference on Software engineering*, pp. 849–852.

Henderson, S. and S. Feiner (2010). Exploring the benefits of augmented reality documentation for maintenance and repair. *Transactions on visualization and computer graphics 17*(10), 1355–1368.

Jäger, N., H. Schnädelbach, and J. Hale (2016). Embodied interactions with adaptive architecture. In *Architecture and Interaction*, pp. 183–202. Springer.

Jones, N. L. and C. F. Reinhart (2017). Speedup potential of climate-based daylight modelling on gpus. In *Building Simulation Conference*, pp. 1438–1447.

Kim, M., X. Wang, P. Love, H. Li, and S.-C. Kang (2013). Virtual reality for the built environment: a critical review of recent advances. *Information Technology in Construction 18*(2013), 279–305.

Koutsabasis, P., S. Vosinakis, K. Malisova, and N. Paparounas (2012). On the value of virtual worlds for collaborative design. *Design Studies 33*(4), 357–390.

Li, J., J. Kim, and X. Chen (2019). Robiot: A design tool for actuating everyday objects with automatically generated 3d printable mechanisms. In *ACM Symposium on User Interface Software and Technology*, pp. 673–685.

Malinin, L. H. (2019). How radical is embodied creativity? *Frontiers in psychology 10*, 2372.

Mallgrave, H. F. (2013). *Architecture and embodiment: The implications of the new sciences and humanities for design*. Routledge.

Mitterberger, D., K. Dörfler, T. Sandy, F. Salveridou, M. Hutter, F. Gramazio, and M. Kohler (2020). Augmented bricklaying. *Construction Robotics 4*(3), 151–161.

Montoya-Olsson, A. S. (2020). *Parametric modeling and optimization of external braced frames for embodied energy and daylight availability*. Ph. D. thesis, Massachusetts Institute of Technology.

Nasman, J. and B. Cutler (2013). Evaluation of user interaction with daylighting simulation in a tangible user interface. *Automation in construction 36*, 117–127.

Newen, A., S. Gallagher, and L. De Bruin (2018). 4e cognition. In *The Oxford Handbook of 4E Cognition*, pp. 1. Oxford University Press.

Peng, H., J. Briggs, C.-Y. Wang, K. Guo, J. Kider, S. Mueller, P. Baudisch, and F. Guimbretière (2018). Roma: Interactive fabrication with augmented reality and a robotic 3d printer. In *Proceedings of the 2018 CHI conference on human factors in computing systems*, pp. 1–12.

Plevoets, B. and K. Van Cleempoel (2013). Adaptive reuse as an emerging discipline: an historic survey. *Reinventing architecture and interiors: A socio-political view on building adaptation*, 13–32.

Rahimian, F. P., R. Ibrahim, J. Wang, X. Wang, W. Shou, and B. Xu (2014). Integrating bim and augmented reality for interactive architectural visualisation. *Construction Innovation*.

Robinson, S. and J. Pallasmaa (2015). *Mind in architecture: Neuroscience, embodiment, and the future of design*. MIT Press.

Rockcastle, S., M. L. Ámundadóttir, and M. Andersen (2018). Ocuvis: a web-based visualizer for simulated daylight performance. In *Simulation for Architecture and Urban Design*, pp. 1–8.

Sanhudo, L., N. M. Ramos, J. P. Martins, R. M. Almeida, E. Barreira, M. L. Simões, and V. Cardoso (2018). Building information modeling for energy retrofitting–a review. *Renewable and Sustainable Energy Reviews 89*, 249–260.

Sutherland, I. E. (1965). The ultimate display. *Multimedia: From Wagner to virtual reality 1*.

Ward, G. J. (1994). The radiance lighting simulation and rendering system. In *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*, pp. 459–472.

Whyte, J. (2002). *Virtual reality and the built environment*. Routledge.