# Integrating Parametric Modeling, BIM, and Building Performance Analysis into Augmented Reality for Architectural Design and Education

KIFAH, ALHAZZAA
Department of Architecture, College of Architecture, Texas A&M University, College Station, Texas
Department of Architecture, College of Architecture and Planning, Qassim University, Qassim, Saudi Arabia

WEI, YAN
Department of Architecture, College of Architecture, Texas A&M University, College Station, Texas

In 2020, about 38% of annual global carbon dioxide emissions come from buildings. Energy-efficient buildings that help mitigate the effects of climate change need a novel strategy to bridge the knowledge gap between construction practitioners and the advancement in building design methodology and environmental analysis. Parameters and forms of the building envelope have a major impact on energy efficiency, and Passive design methods are the most practical and cost-effective means of thermal and energy management in buildings if designed correctly during the preliminary stages. The purpose of this research is to determine whether the current augmented reality (AR) platform can successfully show the potential and significance of parametric design, as well as present a dynamic environmental analysis from the earliest stage of architectural design. In order to enhance the form finding phase of the design process and getting architecture students and professionals aware of the potential of parametric design for design alterations and optimization. The project aims to deliver the subject matter in a clear and engaging manner by the use of AR. In the developed AR app (ParametricAR) users will be able to sense scale, volume, and context, by placing virtual objects in the physical environment. Users will be able to study and evaluate the geometric and spatial design by walking around their building virtually in 1:1 scale. The innovative combination of parametric modeling, BIM, and real-time shadow analysis that was accomplished by ParametricAR served to enhance the user experience and resulted in the production of a package that expanded the user's capacity to develop and assess building forms. ParametricAR was successful in combining parametric modeling, BIM, and shadow analysis into a seamless AR experience that is compatible with the mobile AR hardware that is widely available now.

**CCS CONCEPTS • Human - centered computing ~ Visualization • Computing methodologies ~ Computer graphics ~ Graphics systems and interfaces ~ Mixed / augmented reality • Computing methodologies ~ Computer graphics ~ Shape modelling ~ Parametric curve and surface models**

**Additional Keywords and Phrases:** Augmented Reality, BIM, Parametric Design, Grid System, Real Time Design, Parametric BIM Design.

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## 1 INTRODUCTION

Many countries' governments have instituted energy management strategies in an effort to address the world's energy problems. Energy management techniques have been presented to address the associated challenges, whether the major context is the energy constraint (as in the energy crisis of the 1970s) or environmental issues (as in climate change effects). The suggested long-term and short-term strategies are in conformity with the sustainability framework [1]. According to the International Energy Agency (IEA) 2020 Buildings account for almost 38% of worldwide CO2 emissions each year. Building operations account for 28% of total emissions each year, while building materials and construction (also known as embodied carbon) account for another 10% [2]. As a result, industrialized countries' energy-related carbon emissions constitute thirty-six percent of their total emissions [3]. Heat gain and loss via a building's façade are impacted by both interior (electrical illumination, building equipment, and humans) and exterior (solar radiation, air temperature, and wind) sources. It is essential to make objective energy conservation and daylighting considerations when defining a building's shape, orientation, and enclosure type from the start of the building design process since building and fenestration geometry can indeed effect energy usage. The geometry of a building depends on its form, as well as its structural and climate control systems. It is often accepted that the building envelope's primary function is to provide a protective barrier between the inside and outside of a structure. The building envelope is more than just the exterior skin of a building; it also provides the basis for as much as 80% of the solutions and strategies that seek to decrease energy consumption and improve the thermal and visual comfort of building occupants, paving the way for the development of high-performance buildings that are adaptive to their environment and make use of natural daylight [4], [5].

Shading system is an effective passive design method that reduces energy consumption and improves indoor visual comfort. The well-being and productivity of a building's occupants are directly impacted by the comfort level of its inhabitants, making both energy consumption and visual/thermal comfort critical considerations [6]. Building design and sun position are two factors which affects solar energy and the impact that solar energy has on a building's thermal performance [7], [8]. Three separate blocks' energy usage was shown to respond to changes in envelope size and form. Additional factors shown to improve energy efficiency include the form factor of the building and its optimal orientation [9]. It has been found that there is a distinct urban block shape it might be very energy efficient, and this form exemplifies how forms can be modified to maximize energy efficiency [10]. For optimal energy efficiency, self-shading geometric shapes may be the best option [11]. There are two characteristics that may be used to manage a building's energy usage, and these are the total thermal transfer value and daylighting [12].

Parametric design is generated by the parameter values, and equations are used to establish the relationships between the shapes [13]. Parametric modeling is characterized by the inclusion of both constraints and variable parameters[14]. The term "parametric modeling" refers to the process of creating models that include both fixed and dynamic characteristics[14]. This means that relationships between forms may be established, and the transformational properties of geometries can be stated (mathematically and geometrically). Since about 1990, parametric design has been a factor in the development of architectural design. The conceptual parametric design is a strong tool for designers and architects because it enables live alteration and exploration with such little work being expended on the part of the user. This feature includes the usage of sophisticated mathematical expressions via computer programming, which is one of the most prevalent reasons why students and practitioners are reluctant to begin learning and exploring the parametric world [13].

A visual scripting interface with no need for coding skills has been added to the present program, making it much simpler than it was previously. Any parametric model has to have its bases, also known as its parameters, altered or improved with the use of additional algorithms in order to provide the intended results. There are two forms of parametric design used in architectural design: architectural conceptual parametric design and architectural constructive parametric design [15].

In conceptual parametric design, the form of a particular design is not what is specified but rather its parameters [14]. By adjusting the parameter values, it is possible to construct a variety of objects or configurations. Design Algorithms are efficient due to the fact that they are able to capture a significant amount of variation using just a small selection of numerical values. Computational algorithms have a quality that enables interactive design. The downside is this design technique requires prior experience with programming. Thus, script editors are included in parametric design tools like Maya and Rhinoceros (when used with Mel or Rhino Script, respectively) [15]. However, many current 3D platforms have included a visual scripting interface that does not need users to have any prior knowledge of coding, making it far easier to use than it was in the past.

Constructive parametric design refers to a design approach in which data is included into a predetermined 3D model [13]. This parametric methodology is used in CAD software by companies like Autodesk and Chief Architect, as well as Soft Plan, Nemetschek, and ArchiCAD. Instead of drawing lines, arcs, and other geometric shapes, designers may utilize pre-drawn components like walls, doors, windows, stairs, and roofs. These components come with the option to parametrically adjust the values of the objects, including height, width, thickness, and so on. As a result of this, rather of producing drawings in two dimensions, three-dimensional models are created, which is nowadays standard practice in the field of architecture. This method's objective is to cut down on the amount of time spent drafting and making modifications to 2D drawings. These software tools were developed for standard architectural elements; however, it is not possible to utilize them to integrate non-standard components of contemporary architecture [16].

Building Information Modeling (BIM) is a ground-breaking technology and technique that has significantly revolutionized the manner in which buildings are thought of, designed, constructed, and operated. According to the United States' National Building Information Modeling Standards (NBIMS) committee, BIM is defined as "*a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward*"[17]. BIM is also defined by Van Nederveen as "*A model of information about a building that comprises complete and sufficient information to support all lifecycle processes, and which can be interpreted directly by computer applications. It comprises information about the building itself as well as its components, and comprises information about properties such as function, shape, material, and processes for the building life cycle*" [18]. The constructive parametric design approach is the way to engage with BIM. This method is more restricted than the conceptual parametric design method due to the fact that it works with the geometry of buildings that already have architectural information and properties attached to them. BIM might be built using the constructive technique directly, or it could be produced by transforming the product of the conceptual method into a BIM model, which will be adopted for the study.

The architectural design requires a starting point and a guide, therefore the grid technique has been adopted in this research to provide users with a simple design approach [19], [20]. This research employs the well-known nine-square grid system of Andrea Palladio in order to offer the user with the ability to pull and push the corresponding squares from the grid in order to generate an unlimited variety of building designs, as Andrea Palladio's works shown an abundance of building form possibilities [21], [22]. In the next sections, an in-depth explanation of the grid approach in architecture as well as Andrea Palladio's nine-square grid will be provided.

The aim of the research is to investigate whether or not the AR platforms are able to explain and demonstrate to both students and professionals the power and value of parametric design. The goal of this project is to include a dynamic environmental analysis at the earliest possible level of the architectural design process and to convey parametric design in a manner that enhances students and professionals understanding of significance of the parametric design and environmental analysis. Since AR enhances user engagement and presence [23]. The use of AR technology will improve the parametric BIM design experience. This is due to the fact that users will be able to perceive the sensation of scale, volume, and relation with surrounding [24] by placing the virtual objects in the physical world. The augmented reality will provide users the ability to walk around their produced building form, which will allow them to explore and analyze the geometrical alterations that have occurred. Because of the widespread availability of Mobile AR and its relatively low cost, the mobile device is the example target platform for this study.

## 2 THE GRID METHOD IN ARCHITECTURE DESIGN

Architecture Students in their first year of study are commonly given the classic nine-square grid assignment to learn and investigate the building geometry configuration. This is done so that the students may get an understanding of the building's geometry. All of Palladio's villas were variations on three bay by three bay configurations inside a nine-square grid, which is where Palladio drew his inspiration for his geometric designs (Figure 1) [21]. When it comes to adding and rearranging architectural features, students are encouraged to exercise their creativity as long as they do so within the constraints of a nine-square grid system. Students are not the only ones who use the grid as a starting point; in fact, most architects and designers work with a variety of grids depending on the nature of the project. This is due to the fact that the grid will integrate the architectural layout with the structural design. Timothy Love said that this grid format is the best possible geometric framework for understanding the connection between architectural components and the spatial characteristics of the spaces in which they are located [22]. The grid is equivalent to the syntax of a language. The study of semantics may take place within this framework, which has a very strict definition. Not only is it helpful for attaining harmony, but also, it's helpful for communicating design standards inside a layout when you use a grid system like that. Internal change is made possible by the use of a grid on a smaller size. When applied to a greater scale, the use of a grid enables the design to be developed in a way that is both logical and sensible. Using a grid on a larger scale creates the ground principles for potential building connections. This whole process takes place on two levels: the structural level, and the spatial planning level. The preceding may be achieved by using a basic grid that complies to the golden rectangle's guidelines. This does not imply that this is the only method to design a building. The tartan grid designed by John Habraken offers a high amount of flexibility, therefore bridging the gap between space usage and the restrictions imposed by physical factors [20].

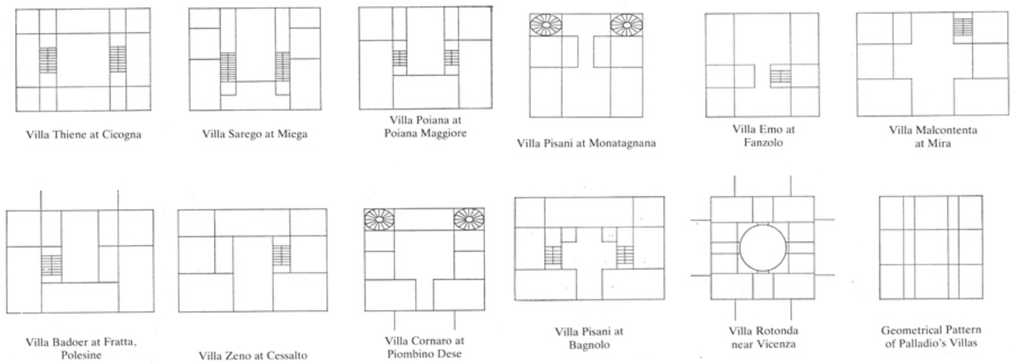


Figure 1. Schematized plans of Palladio's villas. Source:[25]. Credit: Warburg Institute.

## 3 AUGMENTED REALITY

In the Oxford English Dictionary, the term "augment" is defined as "to enhance something by adding to it." Enlarging, extending, or improving the characteristics of physical components are all examples that fall under the category of "making larger." The integration of virtual elements into a real-world environment is the essence of augmented reality (AR). AR makes use of a variety of virtual components in the areas of hearing, sight, touch, and scent to enhance people's perceptions [23]. AR is computer-generated data that is superimposed over the actual environment. The users' experience has been improved across our surroundings in order to make it simpler for them to carry out their responsibilities [26]. The environment in augmented reality is real, but system data and graphics have been overlaid [27]. The actual world can be made better with augmented reality since it is built on top of reality rather than being restricted to virtual settings [28]. AR would allow the most relevant virtual materials to be shown at the proper time and location based on context. In AR, content may be added to the actual world, and existing things can be transformed such that users cannot tell them apart from the real thing [26], [29]. According to Azuma, the three most important aspects of AR are the following [27], [29]:

- The blending of physical and virtual objects
- Interactivity in real time
- Alignment of both physical and virtual objects

### 3.1 AR in Education

A Research has shown some of the positive comments that students have given on AR technology, which enables them to see the whole issue. Another favorable remark was that this technology takes the learner closer to a clear visual comprehension of the problem proposed, given that the conventional method in which these exercises were conducted contains components that cannot effectively be represented [30]. Greater spatial and visualization abilities [31], [32], improved grasp of mathematical ideas and geometric perception [31], [33], better learning performance, and higher information acquisition [34]–[36] are only few of the outcomes of using AR in STEAM education. Additionally, AR has been investigated in a broad variety of subjects, including but not limited to STEM fields such as the study of the English language [37].

## 4 METHOD AND MATERIALS

The prototype for the ParametricAR application has gone through many stages of development (Figure 2.) and makes use of a wide variety of software plugins, all of which are included as components of the Rhinoceros 3D/Grasshopper platform. Grasshopper is a visual programming language and environment that works inside the Rhinoceros 3D computer-aided design (CAD) application [38]. The goal of this research is to determine whether or not the AR platforms that are currently available are suitable for teaching and conveying the power and significance of parametric design in a way that is both straightforward and interactive, and that incorporates environmental analysis in the early stage of the architecture design process. Each of the development stages have its own set of design goals, the overarching goal of which is to ensure that all of the components function together seamlessly and without any conflict (Figure 3.).

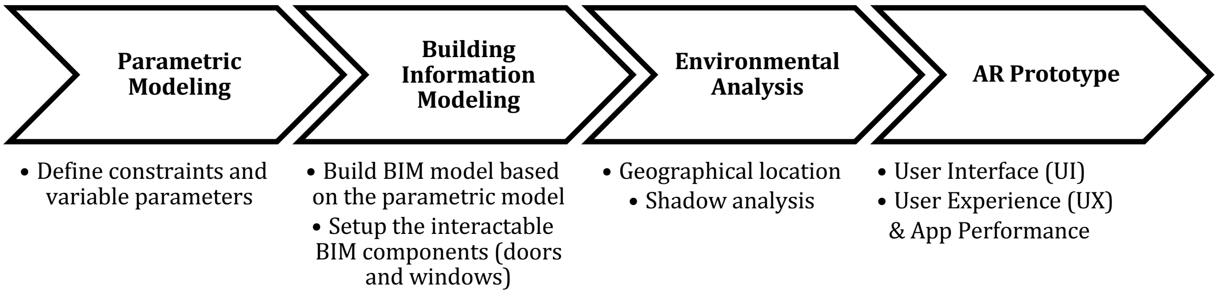


Figure 2. Research Methodology Graph

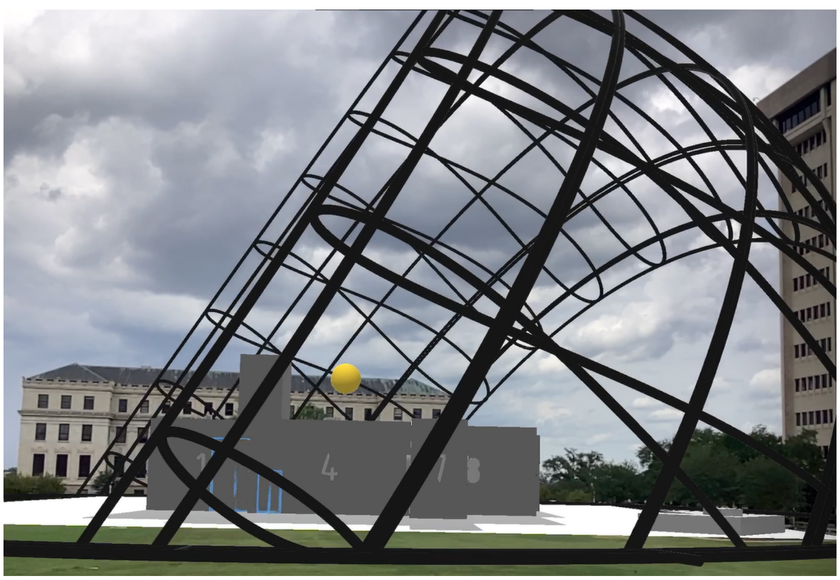

Figure 3. ParametricAR superimposes the parametric building form (gray form), BIM component (doors and windows in blue), shadow analysis (cast shadow on the parametric building form and the white plain floor), and sun path (the black arcs

surrounded the building form and the yellow sphere represent the sun), which are virtual objects, on the physical built environment.

## 4.1 Parametric Modeling

The parametric modeling process has begun with a nine-grid layout that is six meters by six meters and will hold nine boxes (Figure 4.). According to the Architects' Data Book written by Ernst Neufert, the dimension of the grid is based on 10 times the human size, which is equal to sixty centimeters. Grid cell 5's internal points have been picked to serve as a reference for the positioning and movement of the boxes (Figure 4.). In order to simplify the system in terms of the movement direction, grid 5's is only moved along the Z-axis, which controls the height. The X- and Y-axes remain fixed. On the other hand, the design of the courtyard may be accomplished by eliminating the box from grid five. The height (Z) of any box in any grid cell may be made to equal 0 in order for it to be deleted. The middle grids (2,4,6, and 8) are linked to the fifth grid from the rear, and the only axis along which they may move is either the X axis or the Y axis, depending on where the box is located (Figure 4). The corner grids move along the X and Y axes. Each box has its own individual number inputs which is represented by a range of numbers that enable the user to adjust the amount of movement that is permitted along the X, Y, or Z axis (Figure 5). The number slider in Grasshopper is one of the ways to interact with the range in number.

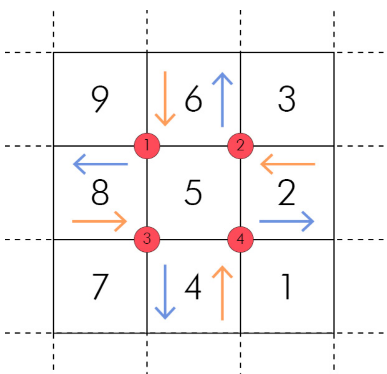

Figure 4. Nine grid layout with Grid 5's points and the middle grids movements

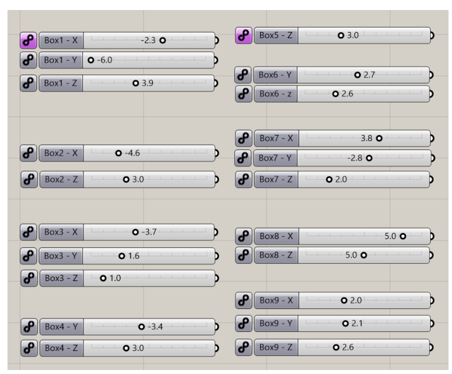

Figure 5. Boxes control number ranges (Grasshopper sliders components)

## 4.2 Building Information Modeling (BIM)

VisualARQ (VA) BIM plug-in for Grasshopper was used to generate the BIM model based on the geometry of the original parametric boxes. The surfaces of the boxes have been organized in a manner that is consistent with their typical orientation in order to differentiate between vertical and horizontal surfaces, as well as the floor and the ceiling. The data that has been structured serves as the foundation for the BIM construct, which was created to enable the needed inputs of VA components.

An innovative approach for windows and doors placement has been adopted, which unifies all of the box floors into a single floor. The procedure then separates the unified floor border in order to position a point on it, which is managed by a number range with values from 0 to 1. The point serves as an input for the placement of the element and is related to VA window and door components. As a result, when the users move the point, the wall or window will shift in the same direction. The users have the ability to vary the height and width of doors and windows, in addition to the height of the windowsill.

### 4.3 Environmental Analysis

The AR apps enrich and add to the physical environment; yet the virtual items need to mix and integrate with the actual world in order to improve the users' immersion in the augmented reality experience. The highly realistic augmented reality experience is not just for providing a high level of immersion; in certain instances, it is required in order to communicate various kinds of information. As a result, the Grasshopper Ladybug tool plugin has been used to power a real-time shadow simulation that has been included into the ParametricAR. The latitude and longitude of the location are required by the shadow feature so that it can accurately compute the sun's direction. The users have the ability to choose the months, days, and hours of the year to investigate various sun paths, which result in a customizable render effect. The shadow function will make it possible for the user to not only design a building shape, but also to conduct an environmental study on the resulting form and optimize it. The precision of the shadow can be quite high since it utilizes the specific geographical coordinates of the location. This will assist the user in making decisions that are based on reliable information.

### 4.4 AR prototype

One of the goals of this project is to develop a prototype for AR software that will allow users to design and analyze their own geometry by superimposing it on real-world settings. The parametric model, as defined by Grasshopper, is linked through the Fologram platform to the real world in the form of AR powered virtual items (Figure 6.). The Fologram is a plugin for Rhinoceros 3D (Rhino) and Grasshopper that utilizes AR to visualize any geometries that are present in a Rhino 3D environment. The capability to adjust the model parameters using a mobile device while simultaneously monitoring the effects of such changes in real time is one of the most important aspects of ParametricAR. As a result, the Fologram is able to provide a real-time synchronization of the Grasshopper definition, and it can do so with many numbers of parameters (Figure 6). This real-time synchronization implies that any modifications to the algorithm in the AR app are immediately updated in Grasshopper and vice versa.

The synchronization of the Fologram consists of two stages: first, the parameter that controls the algorithm is synchronized; next, the final result that displays as an AR object is synchronized. The synchronizable parameters are restricted to native Grasshopper's value list, button, toggle, and slider for numeric values. The algorithm must be properly built-in order to be controlled by these kinds of parameters, which restrict the number of parameters available. Each BIM element (Figure 7.) has parameters to control the position and dimension of the component (Figure 7.). As mentioned in section 5.3 Environmental Analysis, a sun and shadow study has been implemented, the user can turn on the shadow (

Figure 8.) and sun path (Figure 9.) to visualize the location of sun which is controlled by set of parameters: latitude, longitude, month, day, and hour (Figure 9.). Rotation in ParametricAR is not by rotating the virtual model, but it is by changing the orientation (Figure 10) of building which is reflected on the shadow and sun path since the initial building geometry is identical from all sides.

Fologram provides two different ways to position the virtual item, the first of which is by utilizing a QR code. The second method involves the use of artificial intelligence to detect horizontal planes, followed by the location of virtual items in the physical world through a touch on the screen of a smartphone. The second way is the one that ParametricAR has used to empower users with more freedom in moving items without having them to worry about QR codes.

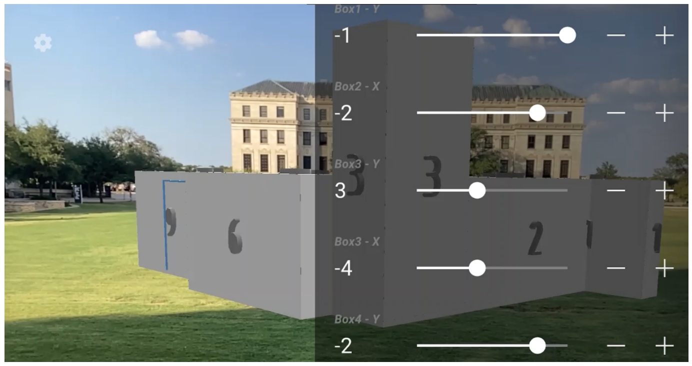


Figure 6. The parametric model and its parameters are synchronized to the Fologram platform that superimposed the model on the physical world.

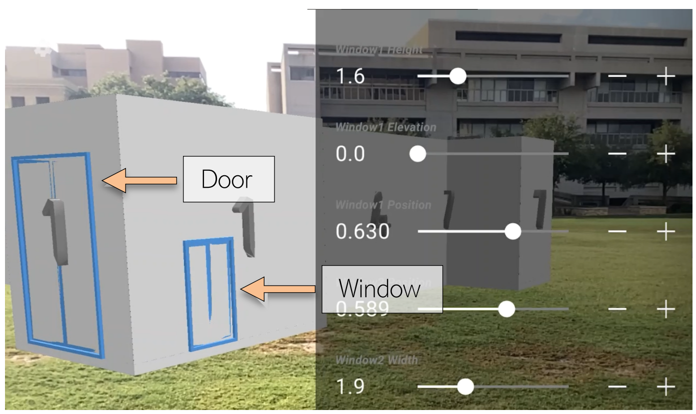


Figure 7. The BIM components (doors and windows in blue) placed on the parametric model, and the BIM components synchronized parameters (height, width, windowsill).

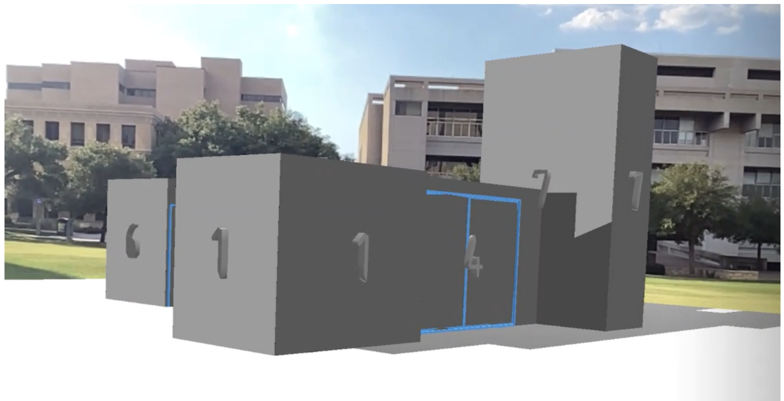

Figure 8. In the shadow analysis, the parametric model casts a shadow on itself and the plain white floor. The shadow matches the shadow of the physical buildings since it uses the exact longitude and latitude of the location for the sun's movement.

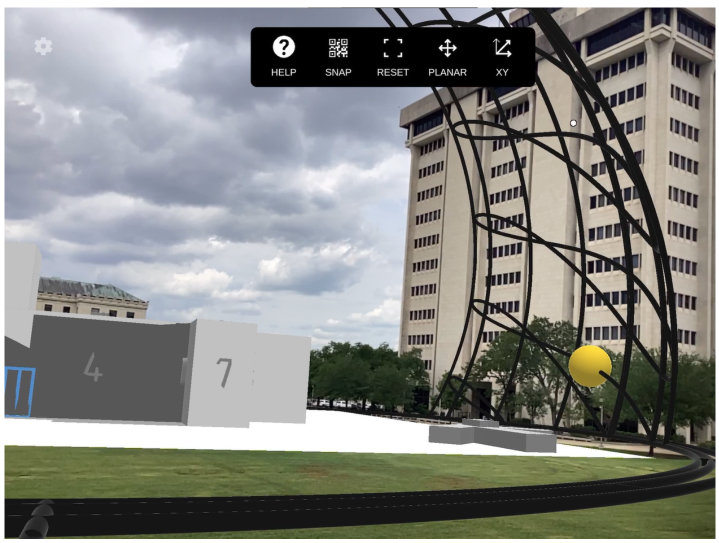


Figure 9. The sun paths are presented with black arcs surrounded the building and dynamic yellow sphere for the sun to visualize the selected time of analysis (Month, Day, Hour).

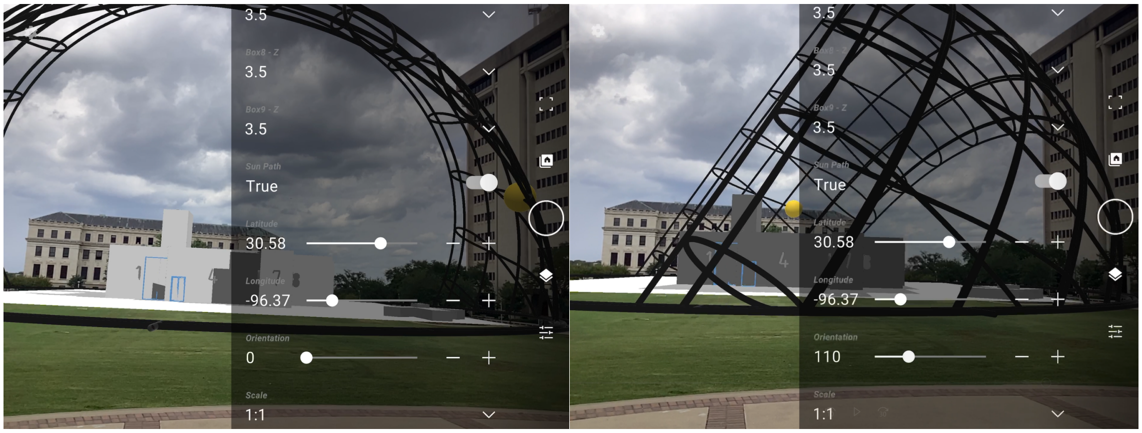

Figure 10. The change of orientation effect on the sun path

### *4.4.1 User Interface (UI)*

The Fologram user interface (Figure 11.) is the only option available for the ParametricAR user interface, and it functions appropriately. The Fologram user interface is lacking in two crucial aspects of user interface design: the capability to be customized and the ability to be organized. Users are left feeling overwhelmed as a result of the large number of sync parameters since Fologram presents all sync parameters that are currently in existence without the option to classify them. However, the developed UI design is legible and well-designed, with features such as the translation menu, which is simple to use since the user must pick the translation axis before completing the translation, and the ability to manage with Rhino layers that are not used in ParametricAR.

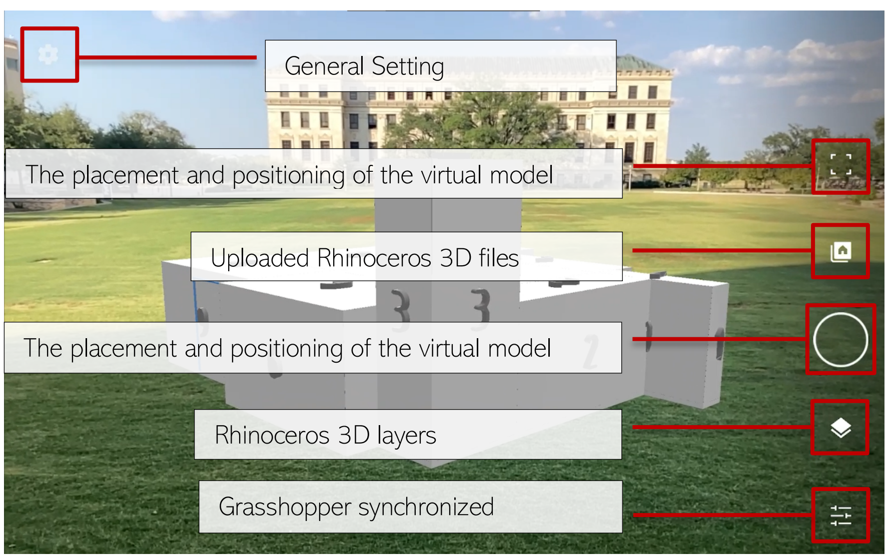

Figure 11. Fologram user interface

### 4.4.2 User Experience (UX) & App Performance

The overall user experience and satisfaction, as well as the performance of the app, have been prioritized in the construction of the ParametricAR, which results in a more seamless experience overall. The parameters, as previously noted, cannot be classified or grouped in any meaningful way at this point. As a result, the number of parameters has been narrowed down to the absolute minimum necessity to achieve the desired effect. A large number of techniques have reached the minimum required for the amount of parameters. There are two reasons for restricting the translation of the boxes to a certain direction in section 2.1 Parametric Modeling: to avoid overwhelming users with movement possibilities, and to decrease the number of parameters. Due to the translation restriction, two of the number sliders were removed from each box, with the exception of the box in the middle. The second tactic is to make the value of the Z-axis based on three choices: 0 for removing the box, 3.5 meter, and 7 meter height. This is done for two reasons: first, it reduces the number of design alternatives, which in consequence reduces the number of parameters; second, it causes the created shape to be a one-floor structure, despite the fact that the building is composed of nine boxes. The introduction of the second-floor option will be a good feature; however, it is not compatible with the AR platform that is now in use. Real-time shadow modeling is a great tool for analyzing and comprehending the building masses, but it is a computationally expensive process, particularly when dynamic changes are included as those provided by ParametricAR. During the process of customizing the architectural form, a switch mechanism has been included so that users may turn off the shadow script if they would want. After that, the shadow script might be activated to conduct an analysis of the building masses. This strategy has improved the app's performance, which has led to a smoother AR experience. Additionally, the number of sliders' increment and decrement value is 10 centimeters. This decreases the superfluous calculation of fractions, which has resulted in an improvement in the app's efficiency. The scale function has been included into the ParametricAR algorithm so that users may choose the appropriate scale for their research and the amount of available empty space in the physical environment.

## 5 CONCLUSIONS AND FUTURE WORK

The feasibility of using parametric modeling and environmental analysis in AR was demonstrated by ParametricAR. The ParametricAR innovatively and successfully merged parametric modeling, BIM, and real time shadow analysis to improve the user experience and produce a package that improved the user's ability to generate and evaluate building forms. It is anticipated that the visualization techniques of ParametricAR would attract students and designers to participate in parametric design and enable them to adapt the design method to their own projects and designs. In addition, it is anticipated that ParametricAR would improve the learning experiences of students and designers throughout the conceptual design phase by providing assistance with form-finding. However, the currently available platforms do not provide enough support for the algorithmic design in a manner that is both simple and readily available. This project was forced to restrict the user's access to the design parameters in order to reduce the complexity of the UI. This was necessary due to the fact that there was no way to classify the data in a manner that would make it simple to comprehend and navigate. As a result, the combination of many plugins resulted in a large number of conflicts, which required solving interoperability issues. It is not possible to save the entire algorithm to the mobile device; rather, the

Grasshopper program on PC has to be running and connected to the mobile device in order to synchronize the parameters. Take a note that Fologram platform was developed specifically for the purposes of fabrication, and not for the purposes presented in this project. Future iterations of platforms and mobile device technology will hopefully be better capable of handling the parametric design algorithm. The capability of the AR platform to sort and arrange the parameters will result in more design parameters, which will lead to more functionalities and interaction with a design that is more complicated. The way to proceed for the application is for it to be tested on architecture students so that an evaluation can be made of its level of engagement and effectiveness in terms of enhancing the form finding design phase and attracting students to the discipline of parametric design. In future work, a new prototype will be developed from the ground up in order to create a dynamic interaction between users, the BIM model, BIM metadata, environmental analysis (e.g., shadow analysis), and the selection of building materials based on the construction types of the materials and their insulation capabilities (e.g., R-value). The real time interaction will result in a large number of building performance conditions which could presented by building loads, embodied energy, embodied carbon, and interior temperature.

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