

PARAMETRIC BIM-BASED DESIGN REVIEW

A Dissertation

by

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ABSTRACT

This research addressed the need for a new design review technology and method to express the tangible and intangible qualities of architectural experience of parametric BIM-based design projects. The research produced an innovative presentation tool by which parametric design is presented systematically. Focus groups provided assessments of the tool to reveal the usefulness of a parametric BIM-based design review method.

The way in which we visualize architecture affects the way we design and perceive architectural form and performance. Contemporary architectural forms and systems are very complex, yet most architects who use Building Information Modeling (BIM) and generative design methods still embrace the two-dimensional 15th-century Albertian representational methods to express and review design projects. However, architecture cannot be fully perceived through a set of drawings that mediate our perception and evaluation of the built environment.

The systematic and conventional approach of traditional architectural representation, in paper-based and slide-based design reviews, is not able to visualize phenomenal experience nor the inherent variation and versioning of parametric models. Pre-recorded walk-throughs with high quality rendering and imaging have been in use for decades, but high verisimilitude interactive walk-throughs are not commonly used in architectural presentations. The new generations of parametric and BIM systems allow for the quick production of variations in design by varying design parameters and their relationships. However, there is a lack of tools capable of conducting design reviews that engage the advantages of parametric and BIM design projects. Given the multitude of possibilities of in-game interface design, game-engines provide an opportunity for the creation of an interactive, parametric, and performance-oriented experience of architectural projects with multi-design options.

This research has produced a concept for a dynamic presentation and review tool and method intended to meet the needs of parametric design, performance-based evaluation,

and optimization of multi-objective design options. The concept is illustrated and tested using a prototype (Parametric Design Review, or PDR) based upon an interactive gaming environment equipped with a novel user interface that simultaneously engages the parametric framework, object parameters, multi-objective optimized design options and their performances with diagrammatic, perspectival, and orthographic representations. The prototype was presented to representative users in multiple focus group sessions. Focus group discussion data reveal that the proposed PDR interface was perceived to be useful if used for design reviews in both academic and professional practice settings.

DEDICATION

To my mother Batool Ali Alandalib and my father Sayed Ahmed Altabtabai.

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NOMENCLATURE

AECO	Architecture, Engineering, Construction, and Operation
BIM	Building Information Modeling
CAD	Computer Aided Design
DCC	Digital Content Creation
FM	Faculty Member
GH	Grasshopper
GI	Global Illumination
GS	Graduate Student
HFT	House for Trees
HMD	Head Mounted Displays
IDE	Integrated Development Environment
IRB	Institutional Review Board
ISD	Integral Sustainable Design
LEED	Leadership in Energy and Environmental Design
MOO	Multi-Objective Optimization
PBS	Physically Based Shading
PDR	Parametric Design Review
sDA	Spatial Daylight Autonomy
So.	Sophomore
Sr.	Senior
TEILab	Texas A&M University Embodied Interaction Laboratory
UDI	Useful Daylight Illuminance
VR	Virtual Reality
WYSIWYG	What You See Is What You Get

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1. INTRODUCTION

Technology affects the way in which we perceive and comprehend the surrounding world (Whyte, 2007). There is a significant need for an integrated BIM, performance-based, and experiential design evaluation methods that may facilitate a better understanding of yet to be realized architectural projects. Game engines allow for better discussions around the ideas of spatial qualities and materiality, thus limiting the possibilities of misinterpretations caused by abstract projection drawings (Fröst, 2002). The basic idea of this research is that advanced computer methods for visualization, such as that found in game engines, may provide for a better setting for design reviews than conventional methods. The functionality of such an interface is referred to in this dissertation as PDR (Parametric Design Review).

1.1. Background

The way in which we visualize architecture, directly by graphical representation methods, affects the way we design and perceive architectural form and performance. Contemporary architectural forms and systems are very complex, yet most architects who use Building Information Modeling (BIM) and generative design methods still embrace the two-dimensional 15th-century Albertian representational methods to express and present design ideas (Gu & London, 2010; Westerdahl et al., 2006). This is a perplexing outcome considering that Alberti himself valued the medium of models more than drawings (Morris, 2006). The Renaissance representational methods of projected drawings may be enough to convey quantity and position of elements in construction documents of conventional design projects. Nevertheless, architecture is arguably more than a set of drawings that mediate our perception and evaluation of the built environment. The essence of architecture is in the direct interactions of humans with their architectural environment (Lynch, 2003; Pallasmaa, 2012; Scheer, 2014). Therefore, there is a need to synthesize an interface which may express the tangible characteristics, e.g., formal and spatial, and intangible qualities, e.g., airflow and sound,

of architectural experience for both architectural inquiry and design research (As & Schodek, 2008).

The systematic and conventional approach of traditional architectural representation uses a limited number of static orthogonal and perspective projections. It is not able to convey phenomenal experience because our entire perceptual system, including motion visualizations, perception of depth, haptic senses, sound, smell, hearing and others needs to be actively engaged with the built environment (As & Schodek, 2008). Paper-based presentation methods cause cognitive challenges in formulating a comprehensive 3D mental image, especially of complex contemporary buildings (Wang & Dunston, 2008). Slide-based presentations, which require constant changes in perspective and orientation, could cause even greater cognitive burden when constructing a spatial image (Taylor & Tversky, 1996). Nevertheless, recent advancement and broader accessibility of interactive Virtual Reality (VR) technology, facilitated by the availability of high-end game engines, has the potential to change the way in which we present and interact with architectural design.

To address the limitations of conventional representation methods of contemporary architecture, there is a need for an effective interface to evaluate design solutions. Generative, parametric, and BIM-based design methodologies have become ubiquitous in contemporary architectural pedagogy and practice (Aish & Woodbury, 2005; Barison & Santos, 2010; Krish, 2011). The new generations of parametric Computer Aided Design (CAD) systems allow for quick production of variations in design by varying design parameters and their relationships (Erhan, Woodbury, & Salmasi, 2009). BIM is a comprehensive database for geometric and non-geometric information, which facilitates the creation and management of architecture, engineering, construction and operation (AECO) data throughout the lifecycle of a building from design to post-occupancy. Parametric modeling facilitates BIM's data management where the alteration of parameters, relationships, and constraints may generate thousands, even millions, of different design solutions.

A great potential for parametric modeling and BIM lies in the field of performance-based design (Oxman, 2007). Performance-based design relies on simulations of form and performance for design feedback (Oxman, 2008). When using parametric modeling or BIM in conjunction with performance-based analysis, the building's performance may guide variation of the formal attributes of design solutions. However, the selection of design options from amongst the vast number of possible design solutions may be problematic. Multi-objective optimization (MOO) could provide a method that facilitates the selection of optimal design options from amongst a set of optimized design solutions. Multi-objective optimal design options are based on performance trade-offs of multiple, mostly competing, performance criteria (Wang, Zmeureanu, & Rivard., 2005).

The integration of VR technology and parametric BIM models is a beneficial trend (Altabtabai & Yan, 2015); however, it is a trend that has not comprehensively addressed the complexity of design evaluation. As a development environment, a game engine could provide a set of tools to enhance spatial awareness, which may result in informed design decisions (Hoon & Kehoe, 2003). A game engine is a set of integrated modules that facilitate the development of interactive environment (Lewis & Jacobson, 2002). Given the malleability of in-game interface design, game-engines may provide an opportunity for the creation of an interactive, parametric, and performance-oriented experience of architectural projects with multi-design options. This may alleviate the problems of presenting parametric models for design presentations and reviews.

This research produced a prototype for a dynamic presentation method of parametric, performance-based, and multi-objective optimal design options for design reviews and then, through focus groups, assessed the prototype in support of a design review. The PDR prototype was achieved by translating an architectural design project into an interactive gaming environment. By using a game engine as a development environment, a novel user interface was designed to simultaneously engage a parametric framework, object parameters, and multi-objective optimized design options and their performances. The prototype couples the developed interface with diagrammatic, perspectival, and orthographic representations in support of a set of functions for design review.

The prototype was demonstrated in a series of focus group sessions to faculty members and students at Texas A&M University. Focus group data were used to evaluate the *perceived usefulness* and *theory confirmation* of the proposed method.

1.2. Research Problem

Collectively, parametric and parametric-BIM modeling software lack functionalities for comprehensive design presentation and evaluation (Altabtabai & Yan, 2015; Scheer, 2014). Current design reviews and presentations of parametric architectural projects, specifically BIM models, do not simultaneously visualize and engage the qualitative and quantitative data necessary to evaluate the performance of a design project. Rather, parametric BIM models are usually presented, and therefore perceived, as static finalized models. Additionally, the advantage of having a parametric model which may generate multiple design options is generally neglected in the review process (Krish, 2011), perhaps due to the vast number of possible design options that a well-conceived parametric framework may generate. Therefore, in design review settings, designers and reviewers face one or more of the following problems:

- The lack of design options and concealment of parametric framework and object parameters - the major advantages of using BIM.
- The lack of real-time walk-through representations using methods such as interactive VR, or game engines, media necessary for qualitative evaluation of a design project.
- The lack of integration of performance-based analysis necessary for quantitative evaluation of a design project.

1.2.1. Lack of design options and concealment of parametric framework and object parameters

“Design is change” (Woodbury, 2010). In conventional presentation and design review methods, design options require massive sets of information. Paper-based presentations will require double square footage of pin-up space if two design options are presented. The number of slides, in slide-based presentations, will significantly

increase with each additional design option. Thus, design options are usually reserved for color, material choices, and furniture layouts, i.e., the design options are not formally disparate. In this research, formal disparity amongst design options refers to the differences in “the shape and structure [amongst design options] as distinguished from [their] substance or material. Also, the manner of arranging and coordinating the elements and parts of a composition so as to produce a coherent image...” (Ching, 2014). Non-formally disparate design options do not take full advantage of BIM capabilities. Furthermore, a thoroughly conceived parametric framework may generate thousands, or even millions, of design solutions. The filtering and selection process to decide which design options to present raises a challenge for designers.

Furthermore, a simple Revit object may contain at least thirty different parameters, such as object type, area, volume, and material, while a BIM model of a single-family house may contain thousands of parameter values. Except for the visible representation of materials and textures, it is impossible to access every parameter of every BIM element when conducting a design review. Although not every parameter of every element may be needed, the unpredictability of what list of parameters may be necessary for the design review raises a challenge for parameter query.

1.2.2. Lack of real-time walk-through representations necessary for qualitative evaluation of a design project

Current design review support lacks an ability to present a scheme in an immersive visualization setting to make possible a qualitative evaluation of the experience of inhabiting the architecture. Virtual walk-throughs allowing real-time navigation and even design adjustments are becoming presentation necessities to aid assessment of the human experience of a design scheme. Usually, walk-throughs are used in addition to conventional presentation media. Examples that utilize walk-throughs are abundant for CAD-based models (Fritsch & Kada, 2004; Fröst & Warrén, 2000; Hoon, Jabi, & Goldman, 2003; Johansson & Roupé, 2005; Jung & Do, 2000; Whyte, Bouchlaghem, Thorpe, & McCaffer, 2000; Yoon, Tutar, & Uddin, 2004). There are few research attempts of BIM-based interactive walk-throughs (Edwards, Li, & Bin Wang, 2015;

Keough, Pejanovi, & Ivanićević, 2009; Kumar, Hedrick, Wiacek, & Messner, 2011; Merschbrock, Lassen, & Tollnes, 2014; Oerter et al., 2013; Yan, Culp, & Graf, 2011). However, while all of the referenced BIM-based examples make use of the geometric BIM model, most of which disregard the non-geometric BIM information.

1.2.3. Lack of integration of performance-based analysis necessary for quantitative evaluation of a design project

Performance-based design relies heavily on computer simulations. Daylighting and energy simulations for example are processor-intensive and may take hours to generate results (Reinhart, 2014; Welle, Rogers, & Fischer, 2012). Design reviews and presentations usually have a limited time-frame which necessitates pre-simulation of performance analysis. Moreover, the multitude of possible design variations when using a generative design platform, such as BIM or parametric modeling software, creates an even greater problem for presenting performance-based analysis as even the simulation results can require massive amounts of digital storage.

Because a comprehensive understanding of a project may not be formulated using a single perspective, architects often use a multiplicity of drawings and representations to convey a design idea. Therefore, these problems are often addressed separately causing the designer to alternate between different visualization methods and software tools to facilitate total comprehension of spatial qualities, parametric properties, and performance analyses. Therefore, there is a need for a user interface which may address the above problems simultaneously while being flexible enough to address future problems as they arise.

1.3. Research Overview

The aim of the proposed study is to define and assess a tailored interface for the presentation of architectural projects utilizing parametric-BIM to enhance the comprehension and experience of parametric-BIM presentations, which can be used for design reviews. The following is a brief description of the research objectives and methodology.

1.4. Research Objectives

The objective of this study is to design and test an innovative tool that facilitates the comprehension and exploration of qualitative and quantitative aspects of multi-option, optimized performance-based building models.

The specific objectives of this proposal are:

1. To develop and assess a new user interface (the Parametric Design Review or PDR), that allows for the experience of multiple optimized design options while simultaneously engaging projective, perspectival, and performance-based visualization methods, through which a parametric design may be reviewed.
2. To create a prototype system for validating the proposed interface. The prototype will provide a vehicle to address the function of the interface in support of design review.
3. To improve the cognition and understanding of complex parametric-BIM, multi-objective building performance-based analysis, and complex spatial qualities.

1.5. Research Methodology

This research envisions a new method through which we may conduct a parametric design review. The new method depends upon PDR, a user interface that facilitates presenting and reviewing architectural design projects. By using PDR, one can comprehensively review projects that may have multiple optimized parametric BIM-based design options and their associated performances. The study is conducted in three phases:

Phase 1 is initiated with a comprehensive literature review of existing methods and technologies for BIM-based design review and presentations. A continuous literature review was conducted throughout all phases of this research. Strong evidence in the literature, suggested that there is a need for the proposed method and that the existence of such a method would be perceived useful. Literature about the design review conventions and intentions was used to develop a list of criteria for an ideal design review support system. Review of literature focused on innovative tools was used to identify gaps in the literature in addressing the criteria and to suggest possible ideas for

the PDR interface. Details of this phase may be found in *Chapter 2*. One of the outcomes of the literature review is the methodology selected for this study, described in *Chapter 3*.

Phase 2 involved the development of a prototype interface, i.e., PDR, that can address the limitations of current methods. The creation of the prototype necessitated the selection of an architectural design project to be used as a test case. A parametric framework for the test case project was created to allow for the generation of multiple optimized design options and their associated performances. Amongst many optimized design solutions, ten design options were selected. The selected design options and their performances were processed for use in a game engine. Finally, a user interface was prototyped in a game engine to assist in presenting optimized parametric design options and their performances. Details of this phase may be found in *Chapter 4* and *Chapter 5*.

Phase 3 utilized multiple focus group discussions where the PDR developed in Phase 2 was demonstrated. Focus group discussions produced qualitative data which were used to validate the PDR. The focus groups were conducted to evaluate the *perceived usefulness* of PDR and to provide *confirmation* that there is a need for such a method. Davis (1989) defines *perceived usefulness* as “the degree to which a person believes that using a particular system would enhance his or her job performance”. Additionally, according to Fern (2001), focus groups may be used as a stand-alone method to *confirm* theoretical notions directly. *Theory confirmation* is the comparing of information gathered from focus groups with the researcher’s prior beliefs (Fern, 2001). Details of this phase may be found in *Chapter 6*.

1.6. Research Significance

This research is expected to conceive and validate a method to enhance the way in which we present and review parametric BIM models by simultaneously achieving the following:

- enabling the designer to comprehensively communicate design intent,
- enabling reviewers to engage with multiple optimized design options,

- allowing reviewers to qualitatively and quantitatively evaluate the performance of each design option.

Ultimately, such a method could improve architectural education and professional practice, leading to improved economic and social environment for the public.

1.7. Overview of Dissertation

This dissertation includes eight chapters that are described below:

- Chapter 1- Introduction: This chapter provides an outline of the study. The *research problem, objectives, methodology, and significance* are discussed.
- Chapter 2- Literature Review: This chapter provides the literature review for *design review, parametric modeling, building information modeling, game engines, performance-based design, multi-objective optimization, and software tools for supporting design review*. The chapter is concluded with a *theoretical specifications and feature specifications* for PDR.
- Chapter 3- Research Methodology: This chapter provides a detailed description of methods used to conduct this research where the different phases of this research are explained.
- Chapter 4- Test Case Selection and Preparation: This chapter provides the details for the selection of the test case – an architectural project used to demonstrate the PDR prototype. The chapter also provides a detailed description of the following: the *parametric framework* that allows for multiple design options to be generated from the test case project; *multi-objective optimization* process that resulted in a set of optimized design options; and different quantitative performance-based *simulations* conducted with the test case project.
- Chapter 5- Parametric Design Review User Interface Prototype: This chapter provides a detailed description of *processing geometric and non-geometric data* generated in Chapter 4 for creating an interactive virtual environment (VE). The chapter also describes the *PDR framework*.

- Chapter 6- Focus Group Experiments, Results, and Discussion: This chapter describes *focus group experiments* where PDR was demonstrated. The chapter provides detailed accounts of the *experiment, results, and discussion* of the focus group experiments.
- Chapter 7- Discussions: This chapter describes how PDR addresses the theoretical specifications for a parametric design review tool.
- Chapter 8- Conclusion and Future Work: This chapter includes a *summary* of this study, the *contribution of the research to the body of knowledge*, and *future work*.

2. LITERATURE REVIEW

The following is a literature review on design reviews, parametric modeling, BIM, game engines, performance-based design, multi-objective optimization, and software tools for supporting design review as the present research is built on top of these technologies and studies. The chapter concludes with a theoretical as well as feature specifications for PDR.

2.1. Design Review

In architecture and design schools, a design review is a significant central method of providing design feedback to students. Other names for design review are critique, crit, or design jury. The origin of design reviews dates to the Ecole des Beaux Arts in Paris where projects were critiqued behind closed doors, i.e., closed jury. Studio masters would evaluate design projects and mark them with a letter grade. In rare occasions, few written notes accompanied these grades. Although there is no solid evidence to support this claim, the design review in its current form, i.e., public jury, is said to be a Bauhaus invention (Anthony, 1991). The current practices of design review methods allow students to communicate their design intent as well as give them the opportunity to develop verbal and presentation skills (Schön, 1985). It also allows anyone to participate in the design review as a spectator or critic, thus contributing directly to the specific design studio, and indirectly to the general architectural education in a design school (McCarthy, 2011). The dialogue in a design review might include praise, critical comments, suggestions for modifications, the offering of design direction, and the discussion of supporting theoretical propositions and theories (Osborne & Crowther, 2011). Figure 2.1 illustrates a typical design jury setting.

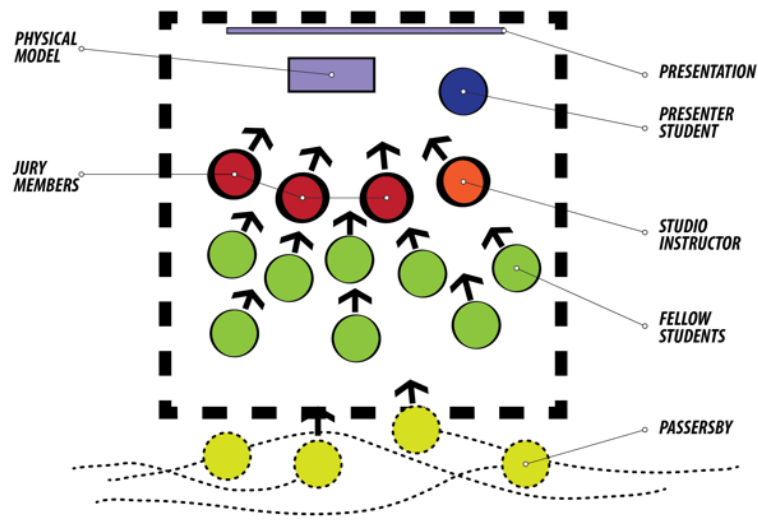


Figure 2.1. A typical design review setting (adapted from Anthony, 1991).

Anthony (1991) has comprehensively documented issues concerning design reviews. Anthony noted that a significant number of students report that they do not think they have learned much from jury comments. Nevertheless, design review is recognized as an integral part of architectural design education where some students find the crit intellectually seductive, and a great opportunity for progressive dialogues. Students value seeing the work of other students in different studios. Seeing other's work helps students reflect on the relative quality of their work and their understanding of the discipline at large (Osborne & Crowther, 2011). The discussions amongst the reviewers may be a rewarding part of design reviews where different ideas and schools of thought may collide (Doidge, Sara, & Parnell, 2000).

The traditional model of design jury, as illustrated in Figure 2.1, typically involves a rigid and hierarchical arrangement of furniture and participants (Osborne & Crowther, 2011). While the purpose of design review is to the benefit of the students in general (Anthony, 1991), one cannot help but question the rigidity of the hierarchical setting of the review space. In a typical paper-based design review drawings may be too small for the students to inspect from a distance, and critics sometimes occlude the drawings. The

scale of drawings might create a visual challenge, and thus reviewers might get very close to presentation boards. For students, the challenge is even greater as they usually sit behind the reviewers and farther away from the presented drawings.

“Architects are designers; they are makers of representations of things to be built” (Schön, 1985). Current design reviews and presentations rely almost exclusively on two-dimensional representation methods (Shiratuddin & Thabet, 2011). Conventional architectural drawings can be a challenging method for understanding a design project (Fröst, 2002). In addition to orthographic drawings, architects have utilized perspectives, axonometric, and physical models to convey design intent (Morris, 2006). In conventional design reviews, a great deal of the presentation time is spent on clarifying complex spatial qualities in the plan/section/elevation. To gain a comprehensive understanding of a design project, a new user interface –one that allows for qualitative and quantitative design evaluation– is necessary for architectural design reviews and presentations.

Current representation methods for design reviews may fit into two main categories, that of the conventional representation methods and the more recent digital representation methods. Regardless of the representation method format, in a design review, students are expected to communicate their design idea effectively and clearly.

2.1.1. Conventional representations

Although they may be digitally conceived, the outcome of conventional representation methods is physical, i.e., printed or hand drawn presentation boards and physical models. Drawings and printed media may include, but not be limited to, plans, sections, elevations, perspectives, diagrams, and axonometric representations. Physical models may serve different functions and convey different attributes of the design intent. Massing, sectional, site, spatial and detail mock-ups are a few examples of physical models.

Printed media

Conventional representation methods allow for a concurrent display of information. This juxtaposition of different representations and information is a strength exclusively associated with traditional design review methods (Dave, 2000; Roberts, 2004). Therefore, reviewers can roam around and examine the drawings in any sequence (Locsin, 2007). This freedom of information intake may allow reviewers to visually scan traditional architectural presentations going from macro- to micro-details (Porter, 2003).

Limitations of conventional representation methods may be summarized in the following: (a) Views are static and predefined and therefore inhibit the interrogation of the project from other points of view not specified by the designer (Kalay, 2004); (b) The methods may lack information and therefore raise formal clarification questions or technical representation questions, which may not contribute to the dialogue; (c) For complex formal geometries, one could easily lose orientation; (d) Mistakes may require reprinting the whole presentation, and therefore contribute to the already problematic amount of solid waste in academia (“Facts About Consumption and Waste - National Wildlife Federation,” n.d.); (e) Individually, most two-dimensional representations cannot convey design intent unless combined with other representations (Yee, 2012). Thus a large set of drawings is usually needed to review a design project comprehensively.

Perhaps the major limitation of conventional representation methods, which this research is trying to address, can be explained by Greenberg (1974):

For architects the ability to simulate motion is highly useful. One of the principal concerns of architectural design is space: the internal spaces of a building and the external space of the building and its setting. One does not react to space from a static position, as one might view a painting. To obtain a deeper understanding of architectural space it is necessary to move through the space, experiencing new views and discovering the sequence of complex spatial relations.

This research aims to simultaneously make use of the advantages associated with printed media and address printed media's limitations by using advanced computer-based visualization. Similar to printed media, a computer-based interface for design review could juxtapose multiple representations to allow for concurrent display of information. To address printed media's limitations (a) and (b) dynamic representations could allow for freedom of interrogation and inspection of the presented model from points of view that were not predefined. To address limitation (c), representations could constantly highlight the user's location and orientation in the VE. A digital method could dramatically reduce the amount of solid waste produced by architectural schools due to the method's exclusive reliance on high-resolution digital displays to review design projects, addressing limitation (d). Additionally, a computer-based interface for design review could produce a multiplicity of real-time generated two, as well as, three-dimensional representations to communicate design intent. Thus, it may address printed media's limitation (e). The multiplicity of representations may rely on different methods of visualization to communicate spatial characteristics, phenomenological qualities, and analytical properties. Finally, this research aims to address the limitation expressed by Greenberg (1974), via the inclusion of real-time walk-through visualization mode. All of the above when combined with the need to review multiple design options, may raise even a greater challenge.

Physical scale-models

Well-crafted physical models can attract a lot of attention and admiration in a design review. Morris (2006) identifies different reasons for reviewers' attraction to physical models. Models communicate well particularly to non-architects because they are the first manifestation of a design that one can readily apprehend. Because of their small scale, models empower the viewer and thus creating what Morris describes as the "King Kong Effect." Models are familiar in the way in which they might resemble toys, and therefore trigger memories associated with childhood. The model allows for the whole to be apprehended before the part, thus communicating the "big idea." Finally, because it is

a physical three-dimensional artifact, the model leaves less room for spatial interpretation when compared to abstract orthographic drawings.

Morris (2006), identifies the following limitations of three-dimensional physical representations, i.e., physical models: (a) Model making is a time-consuming process; (b) Multiple models are needed to convey design intent at different scales; (c) It is hard to assess materiality and existing environment, context, settings, which may lead to misinterpretations; (d) It is hard to archive and/or share a physical model; and (e) It is awkward to revise and/or update. Furthermore, the following points may also be considered limitations of physical models: (f) Models are non-experiential, static objects do not always convey the phenomenological aspect of a design project; and (g) 3D printed models are expensive and non-interactive.

A computer-based design review interface could address the limitations of physical models. To address limitation (a), the method could rely on digital models that do not require the additional time associated with physical models when cutting, gluing, or painting materials. By using a computer-based method one could embed multiple levels of abstraction in the digital model to communicate design intent at different scales, a feature that could address limitation (b). To address limitation (c), a computer-based interface could utilize a multiplicity of visualization methods to assess materiality, existing environment, context...etc. Because we rely on software and digital media, archiving and sharing digital models is significantly easier than physical models, a quality that may address limitation (d). To address limitation (e), although parametric models may take a long time to setup, once the parametric framework is thoroughly developed, the adjustment of design solutions may be less time consuming or even instantaneous. To address limitation (f), a digital method could rely on dynamic models that one may navigate via virtual walk-throughs to evaluate the phenomenological aspects of a design project. Finally, to address limitation (g), the development of PDR could rely on free of charge, or heavily discounted software for students to create design review presentation.

2.1.2. Digital representations

The word “digital” in *digital representations* refers to the outcome of the representation method, even if images in the presentation are manually conceived and executed. For example, scanned hand drawings and photographed physical models are therefore considered digital. Current digital representation methods usually rely on digital slide shows, i.e., PowerPoint presentations, predefined walk-through, and animations.

The limitations of these representation modes are: (a) Predefined views chosen by the designer, thus many aspects of the design, successes, and failures, maybe occluded; (b) scripted animations; (c) a linear presentation mode; (d) constant switching between slides, i.e., lack of information juxtaposition; (e) minimal information per slide, thus the need for many slides (Tufte, 2006). To go even further, Tufte (2006) identifies the following PowerPoint presentation cognitive style characteristics: foreshortening of evidence and thought; low spatial resolution; an intensely hierarchical single-path structure as the model for organizing every type of content; breaking up narratives and data into slides and minimal fragments; rapid temporal sequencing of trivial information rather than focusing on spatial analysis; and a preoccupation with format, not content. For Tufte (2006), PowerPoint is presenter-oriented, not content-oriented nor it is audience-oriented.

This digital presentation format can be awkward for some reviewers, and even more so for students. Architects are trained to correlate and juxtapose different orthographic drawings and perspectives to comprehensively understand a design project, which is very difficult when using a slide show. A digital slide show created by one individual may not provide the information in the order or time frame that suits the needs of each reviewer and/or student (Locsin, 2007). Additionally, the constant change in perspective and orientation could cause a cognitive burden when constructing a 3-dimensional spatial image (Taylor & Tversky, 1996). Nevertheless, PowerPoint may have an advantage over printed wall displays where the audience can focus on the large projected image (Roberts, 2004).

This research aims to address the above limitations of current slide-based design reviews. To address limitations (a) and (b), PDR could include a set of representations that are not predefined or restrictive, e.g., interactive walk-through, which may reveal failures of design decisions. By using multiple viewports to reveal multiple juxtaposed representations simultaneously, a digital representation method may address limitations (c) and (d), where one may inspect information in a non-linear fashion. To address limitation (e), a digital method could layer information where one may reveal only appropriate information to the task at hand.

Computer-aided architectural design has significantly improved the design process through simulation of space, form, and performance. The question remains, however, if everything designers make in the digital environment is facilitated by the ability to thoroughly navigate the environment and interrogate geometry in CAD and BIM, why are design reviews still conducted using Bauhaus or even Beaux Arts methods? Why are critics and students prevented from this thorough scrutiny and experience of architectural design in the VE? The answer to this question may lie in the inability of current representation methods to withstand the amount of information provided by current design and simulation platforms.

It is evident that design review methods have not significantly, or even noticeably, evolved since the Beaux Arts (Anthony, 1991). Anthony's book was published in 1991, and yet her explanation of how design reviews were conducted is still valid as of the writing of this research. Even more striking is the fact that design representations and presentation boards methods have not changed in the last 25 years. The main difference is that now representations are more convenient to edit and easier to achieve due to advancement in computing power and computational methods. To challenge the design process, one must challenge design representation as it is, without a doubt, a guiding part of the design outcome.

The way in which architectural design reviews were conducted at the Beaux Arts is directly related to the tools that architecture students were using. Plans, sections, elevations, and so on, were the design generation and problem-solving tools, i.e., to

design a building students had to draw these representations to arrive at a sound solution manually. Contemporary design generation and problem-solving tools have moved beyond orthographic representations. More time may be spent on inspecting the model than on creating geometry (Bilda & Demirkan, 2003). Therefore, a new design review method may need to reflect on the tools used in the design process for the reviewers to fully comprehend a design project. PDR could bring to the design review the same level of navigational freedom and design scrutiny available solely to the designer and only during the design process (Roberts, 2004).

The intent of design juries is feedback and constructive criticism to students, i.e., improve design skills (Anthony, 1991). Therefore, an equal and uniform visual access to representations should be provided to all design review participants, reviewers, and spectators. It is not uncommon for a jury to ask questions during the design review to clarify spatial configuration and architectural representations which may not directly benefit students or the overall discussion but rather reflect on the lack of visual and information coherence of utilized representations. One might argue that students' abilities, or lack thereof, are to blame. However, it could as well be due to the spatial and geometric complexities allowed by modern parametric, CAD and BIM, systems (Dave, 2000; Mitchell, 2005), or lack of holistic overview of design projects due to limitations of design review representational methods (Roberts, 2004). As architecture deviates from traditional forms that are harder to express using projective drawings, representation needs to shift from dictating architecture to providing an interface for decision making (As & Schodek, 2008).

2.2. Parametric Modeling & Parametric Building Information Modeling

Parametric modeling allows for variation in design using parameters and constraints between different model elements, which enables generative design exploration of forms that automatically update due to change in parameters, performance, or context (Aish & Woodbury, 2005; Oxman & Oxman, 2014). Woodbury (2010) describes parametric modeling as follows:

Rather than the designer creating the design solution (by direct manipulation) as in conventional design tools, the idea is that the designer establishes the relationships and edits the relationships by observing and selecting from the results produced. The system takes care of keeping the design consistent with the relationships and thus increases the designer ability to explore ideas by reducing the tedium of rework.

Generative and parametric design methodologies have become ubiquitous in academia and professional practice (Krish, 2011). Due to the mathematical nature of parameters, parametric modelers may be enhanced by the addition of performance-based analysis tools. An intelligent parametric framework may respond to, for example, climatic, structural, and acoustic simulations. For example, simulation results of how much solar radiation a window receives may constrain the width, height, and type of the window used.

BIM is an intelligent and comprehensive database for geometric and non-geometric information, which facilitates the creation and management of AECO data throughout the lifecycle of a building from design to post-occupancy. In contrast to CAD systems which only store the geometric definition of an object, a BIM model links the three-dimensional representation of an object with a real-time database of parametric properties (Garber, 2014). For example, specific, three-dimensional geometric and non-geometric information such as areas, volumes, cost data, materials, and component count are included in the database. In addition to element properties, a BIM database may also embed relationships between elements. For example, a window object contains a reference ID to the wall hosting the window, and a door object contains a reference to the two spaces connected by the door (Yan et al., 2011; Wu, Zarrinmehr, Asl, & Clayton, 2015).

BIM's parametric constraints and relationships amongst model elements allow for quick iterations of design updates. Due to theoretically thorough parametric properties embedded in BIM elements, there is a great potential in the integration of BIM with

different performance-based simulations, such as energy and acoustics simulations and game engines (Altabtabai & Yan, 2015; Altabtabai, Mansour, & Yan, 2016; Asl, Stoupine, Zarrinmehr, & Yan, 2015; H. Kim, Asl, & Yan, 2015; Rahmani Asl, 2015; Rahmani Asl, Zarrinmehr, Bergin, & Yan, 2015; Wu & Clayton, 2013).

Conducting design reviews using current parametric or BIM models is a challenge. Collectively, parametric and parametric-BIM modeling software lack functionalities for comprehensive design presentation and evaluation (Altabtabai & Yan, 2015; Scheer, 2014). Current parametric and BIM authoring software only allow for quantitative and non-experiential qualitative evaluation methods, i.e., evaluation of geometric properties, composition, and proportions. *Experiential qualitative evaluation methods* in the context of this research refers to interactive real-time walk-throughs of the virtual model using high-end graphics. Additionally, access to a BIM database may not be possible during conventional design reviews.

Furthermore, a thoroughly conceived parametric framework may generate thousands, or even millions, of design options. Although the new generations of parametric and BIM systems allow for this dynamic and quick production of formal variations, the creative exploration of design scenarios is usually excluded from design presentations (Erhan et al., 2009). Parametric and BIM models are typically presented, and therefore perceived, as static finalized models. Design options in conventional presentation and design review methods require massive sets of information that may prove to be a challenge for paper-based as well as slide-based design reviews.

A prototype of a working interface could comprehensively highlight the advantages and addresses limitations associated with parametric and BIM models for design reviews. A new method could allow for simultaneous evaluation of quantitative and qualitative building performances by using experiential, non-experiential, and analytical representations. Additionally, the research aims to provide access to BIM database while conducting a design review. Rather than presenting a static model the study aims to integrate the parametric framework as an essential part of the design review where one may comprehend the parameters, rules, and performances that have guided the design

process. In addition to presenting the parametric framework, the new method could allow for the layered inclusion of multiple design options where one may alternate amongst design solutions at will.

2.3. Game Engines

A game engine can be used as a platform for the creation of interactive environments. Game engines contain an integrated collection of modules that are necessary to simulate an interactive environment and are offered to software developers as an aid to creating computer games. For example, these modules handle input (e.g., keyboard and mouse), output (e.g., rendering and sound), and generic physics/dynamics for the game environment (Lewis & Jacobson, 2002). In gaming environments, geometric objects are often modeled and textured to a great degree of detail. This necessity of greater geometric detail gives BIM-based models an advantage over the CAD-based counterpart. By using BIM, a high level of geometric comprehensiveness and information required for an interactive environment can be rationalized and embedded in BIM models (Hoon & Kehoe, 2003).

Rendering is the process of converting 3D models into an on-screen 2D image. Real-time rendering is usually achieved at a viewport refresh rate of 30 or 24 frames per second (fps). Real-time rendering in a gaming environment supports textures, shading, and shadows to add realism to the environment. Real-time global illumination (GI) is a new addition to game engines where light rays may bounce from one surface to other surfaces (indirect light) and are not limited to light that hits the surface from the main light source (direct light). Indirect lighting allows for greater realism and atmosphere in the VE as adjacent surfaces affect each other similar to real life (“Unity Manual,” 2015). In this research, I address limitations of current design review methods by using a game engine to facilitate comprehensive communication of multiple design options. The possibilities for interaction in a virtual game world are vast. As a medium, game engines can simulate nearly every other type of media (Gauthier, 2005). Therefore, game engines have the flexibility and extensibility required for creating an interface through which one may present multiple design options using various representational methods. Because of

the abundant availability of references for Unity®, I used that game engine to create the prototype for the proposed research using Unity 5.5.

Unity is a game engine that allows for a diverse set of interactions. The engine runs on Windows, Mac OSX, and currently, a beta version of the engine is in development for Linux. Using C# or JavaScript language, additional custom interaction codes may be added for a specific functionality. The engine comes with Microsoft Visual Studio® programming IDE (integrated development environment) to write and compile code. Unity is a multi-platform engine, meaning it is possible to create an interactive environment that may be accessed from different devices such as desktops, mobile, game consoles, and the web.

2.4. Performance-Based Design

Performance-based design relies on simulations of form and performance (Oxman, 2008). A wide range of analysis and evaluation tools have been developed for different architectural simulations such as daylighting, physics, energy, and structural analysis. For example, Ladybug®, Honeybee®, and DIVA® are plug-ins for Grasshopper which facilitate daylighting and energy simulations. The simulation results may output graphical representations or numerical data. The data may then be used to conduct additional analysis. When using this data in conjunction with parametric modeling or BIM, the building's performance may guide variation of the formal attributes of design solutions rather than merely report the results of simulations for the sole purpose of providing feedback. That is, a performance-based analysis may become the source of formal synthesis in addition to the ability to report analysis data.

2.4.1. Performance-based design and evaluation frameworks

A building's performance is contingent upon a multiplicity of parameters and their values and itself is expressed as very large datasets (Oxman & Oxman, 2014). Balancing performance based on multiple criteria is theoretically problematic (Radford & Gero, 1988). There have been many attempts to define frameworks explicitly to aid in a comprehensive evaluation of architectural form and performance. The earliest surviving

written effort on quantifying architectural design evaluation is accredited to the Roman architect Vitruvius in the 1st century BC (Pollio, 1914). For Vitruvius, a successful building should follow and be evaluated by the three principles of *firmitas*, *utilitas*, *venustas*. *Firmitas* had been translated, almost unanimously, to *durability or strength*. *Utilitas* has been translated to convenience, functionality, or utility. Meanwhile, *venustas* had been translated to *aesthetics or beauty* (Darmawan, 2009).

For Vitruvius, architecture depends on *order* which brings unity between the part and the whole. Accordingly, the order depends on symmetry and proportional systems. Vitruvius constructs his claim by comparing architecture to the human body. Interesting enough, he goes even to specify functions that may correspond to different light directions such as eastern light for bedrooms or libraries, and northern light for galleries (Pollio, 1914). Vitruvius also reflects on the bimodality of architecture, specifically when discussing economic constraints of materials and site which can directly affect the formal qualities of a building.

There are many different frameworks, opinions, theories, and practices claiming to be the most appropriate or comprehensive evaluation methods. For example, there are theories about design guidance through sensuality/phenomenology (Bachelard, 2014; Pallasmaa, 2012), green and sustainability (DeKay, 2012; Yeang, 2015), ecologically sound solutions (Mostafavi, 2010), formal and mathematical aesthetics (Lynn, 1999), and parametrically derived conceptions (Schumacher, 2011; 2012). However, considering the many disparate schools of thought, the evaluation stance may need to be addressed by the design studio instructors, and per each assigned design project.

A relatively careful and comprehensive set of criteria in the context of 20th century scientific and rational thought has been composed as Building Systems Integration (Rush, 1986). Rush defines performance as “the measurement of achievement against intention.” In other words, it is the measure of client satisfaction with the building. Rush outlines six performance mandates—spatial performance, acoustical performance, thermal performance, air quality, visual performance, and finally building integrity. Each of the performance mandates is defined by physiological, psychological, sociological,

and economic needs. According to Rush, this complexity allows the performance mandates to contain a large or even comprehensive list of building performance criteria, and therefore it may be applied to the diverse range of architectural projects.

The first five performance mandates consist of interior occupancy requirements, and parameters of health, safety, and well-being. The last performance mandate - building integrity – is the intention of protecting the building’s appearance and its mechanical and physical properties from human-made or natural environmental degradation. It includes accommodation of structural loads as well as durability and addressing degradation due to weathering. Each of the mandates has a benchmark established by accepted limits for the type of occupancy. The benchmarks may be expressed as codes, standards, and guidelines for the design and construction of architecture, or may be less formally established.

Additionally, Rush accepts the fact that according to the function of the building or space, a particular mandate might have priority over other performance mandates. For example, monuments require increased attention to *building integrity* against weathering and deterioration, while a theatre may require greater attention to *acoustical performance*. Table 2.1 is an example by Rush of different building types’ demand for various performance mandate priorities.

Performance Priorities for Various Building Types						
Building Type	Spatial	Acoustic	Thermal	Air	Visual	Integrity
Small Office	✓		✓			
Large Office	✓	✓	✓	✓	✓	
Multi Family	✓	✓				✓
Single Family	✓		✓			✓
Stores					✓	
Shopping Centers	✓		✓	✓	✓	
Hotel/Motel	✓	✓	✓			✓
Elementary Schools	✓	✓	✓	✓	✓	✓
Secondary Schools	✓	✓	✓	✓	✓	✓
Warehouses						
Assembly		✓		✓	✓	
Clinics	✓			✓	✓	
Nursing Homes	✓		✓	✓	✓	✓
Hospitals	✓		✓	✓	✓	✓

Table 2.1. Performance mandate priorities according to building type. Adapted from (Rush, 1985).

Another issue is style. Lightner (1992) argues that since the rise of the postmodernist school of thought, it has been challenging for architects to agree about style. Lightner also suggests that, if still alive, influential authors such as Vitruvius or Alberti would have a hard time writing even a single book treatise (Lightner, 1992). Unlike other quantifiable criteria, aesthetic performance is the hardest to measure and evaluate. For contemporary architecture, standards for aesthetic performance and beauty are not universally accepted. Rather, some argue that aesthetics are unique to the problem and contemporary culture (Scheer & Preiser, 1994). “We are in a time when anything goes and there is no basis for a manifesto – postmodern has come to, ultimately, no meaning.” (Balmond, Smith, & Brensing, 2007).

Because of its subjective nature, aesthetics performance may be measured through intentional design decisions that logically correlate between design organizational strategies and the designer's worldview. If a building satisfies objective criteria, design intentionality may facilitate the way to evaluate its aesthetics. If the aesthetics of a design project come from a logical system that may be identified by the designer, then the project is aesthetically successful, though it may not necessarily be aesthetically pleasing. An aesthetically successful design may follow a certain logic or world view. The design solution may be considered aesthetically successful because it adheres to the intentions of the designer's world view, i.e., the aesthetics may follow a world view that questions architecture through the aesthetics of the grotesque, ruination, or destabilization, to name a few (Alonso, 2010; Pallasmaa, 2011).

2.4.2. Performance-based daylighting evaluation dashboard

Because daylighting is often considered as a major component of green building design (Leslie, Radetsky, & Smith, 2012), the decision was made to include daylighting analysis as the performance-based example for the proposed interface. Daylighting is “a process by which direct sunlight and diffuse daylight are reflected, scattered, admitted and/or blocked to achieve a desired lighting effect” (Reinhart, 2014). A more qualitative definition of daylighting is “*The interplay of natural light and building form to provide a visually stimulating, healthful and productive interior environment*” (Galasiu & Reinhart, 2008). Reinhart (2014) classifies a space as daylit if the amount of available daylight specifically satisfies the function of the space.

Reinhart (2014), makes a distinction between the quantitative and qualitative evaluation of a building's daylighting performance. He suggests that quantitative evaluation of daylighting should be based on performance metrics that fit in the categories of *daylight availability, energy, and comfort*.

Different research outcomes suggest different dashboards for daylight evaluation (Leslie et al., 2012; Reinhart & Wienold, 2011). A daylighting evaluation dashboard is a simplified yet comprehensive set of analyses which may contain graphical representations as well as numerical calculations of several performance metrics. My

research will adapt the daylighting evaluation dashboard as suggested by Reinhart & Wienold (2010). The dashboard facilitates communicating: daylight availability performance via reporting Spatial Daylight Autonomy (Mohsenin & Hu, 2015), and Useful Daylight Illuminance (Nabil & Mardaljevic, 2005); energy performance via reporting Energy Use Intensity, Annual Utility Cost, and Monthly Utility Cost; comfort performance via reporting Glare probability temporal map.

Qualitative evaluation of daylighting is difficult to measure and quantify because it is subjective and perceptual (Reinhart, 2014). A well daylit space is sometimes based on personal and cultural preferences. Thus, a framework for the qualitative evaluation of daylighting does not currently exist (Reinhart, 2014).

By reporting performance-based analysis for multiple design options, one may better communicate consequences of a design decision in comparison to the other options and therefore elicit informed criticism from reviewers. During the design review, priority may be given to a design solution that is based on trade-offs amongst the three performances of *daylight availability*, *energy*, *comfort*. In this study, it is assumed that the designer and design reviewers will qualitatively evaluate the aesthetics of design solutions, and therefore, no quantifiable metrics, or attempts to quantify aesthetics, will be discussed. Alternatively, quantitative design performance may be ignored during the design review where focus may solely be given to personal expression and aesthetics, if quantitatively the design solutions have similar performance. It is important to note that the proposed tool, does not dictate any specific performance mandate to evaluate a design solution. It is merely a method that facilitates a new way of comprehending design projects. Although daylight availability, energy, and comfort are adapted, any other criteria may substitute these categories or live with them side-by-side.

Performance-based design relies on computationally expensive simulations. Simulations necessary to measure daylight availability and energy are process intensive which may take hours to generate results (Reinhart, 2014; Welle et al., 2012). For multiple design options, time constraint is even more problematic. Simulating the results of various design alternatives ahead of a schedule review can assure that the results are

available, but limit the number and range of alternatives that may be discussed. Because design reviews have a limited time-frame, the strategy in my research is to overcome this limitation by pre-simulating computationally expensive analyses.

2.5. Multi-Objective Optimization

“The function of a building as a whole is established by its program, so the performance of elements and subsystems must be evaluated relative to the program. Good performance is a matter both of adequacy in a role and of economy of means.” (Mitchell, 1990).

Schön (1985) describes architecture as a bimodal profession. On the one hand, it is considered an *artistic expression* rooted in historically significant buildings and monuments. On the other hand, it is considered a *social function* by providing shelters within which life may flourish and work may get done. As artists, architects are form givers constrained by resources and economic factors. As functionalists, architects are holders of particular knowledge capable of achieving solutions for an individual and/or a communal necessity (Schön, 1985). Artistic expression and social functions tend to live in conflict in architectural practice and education where each mode may suggest a different solution to an architectural design problem. These bimodal views also make it difficult to arrive at a framework through which one may reliably select one design option over another.

Artistic expression and *social function* may provide goals and constraints to guide architectural design solutions. The former may contain a subset of mostly qualitative criteria, while the latter, for the most part, contains a subset of quantitative criteria. In conventional methods, the exploration of a design solution space is based on the manipulation of design variables, experience, rules of thumb, and comparisons with benchmarks (Reinhart, 2014; Wang, Zmeureanu, & Rivard, 2005). This process is time-consuming, which inhibits the exploration of the vast design solution space and confines the number of iterative alteration and feedback loops (Rahmani Asl et al., 2015).

Some theorists define architectural design as a problem-solving process. To solve a problem, designers must define a series of actions through which they can arrive at a

solution (Simon, 1996). Performance-based design optimization often involves a multitude, mostly competing, performance criteria (Wang et al., 2005; Yan, Asl, Su, & Altabtabai, 2015). Designers do not typically know in advance the exact goal state or whether a candidate solution is, in fact, a viable solution (Chan, 1990). The design solution process in architecture, professional practice and academia, is essentially similar to traditional optimization or search processes (Gagne, Andersen, & Norford, 2011). Gagne sees that earlier studies that aim to categorize search methods during the design process are analogous to optimization algorithms. However, Gagne highlights that, unlike an optimization algorithm, architects can never fully explore the entire search space for optimal solutions. Because there is an infinite set of solutions to any design problem, designers must always limit their search to a small subset of possibilities (Gagne et al., 2011). Due to their mathematical nature and clearly defined objective function, parameters, and constraints, traditional optimization problems are considered *well-defined* (Gagne et al., 2011). The goal of a well-defined problem is clear where one may aim to minimize or maximize a given objective function within a given search space (Simon, 1977). In contrast, an architectural design problem is considered an *ill-defined* problem because the problem is almost always multi-dimensional—multi-objective—and therefore, too complex to be comprehensively defined (Chan, 1990; Eastman, 1969). It is near impossible to define a clear set of specific objective functions because when faced with a design problem, a designer may wish to meet many, sometimes hundreds, of goals, many of which are subjective such as aesthetics and client preferences (Gagne, 2011).

During the design process, architects come up with initial set of design ideas based on a set of initial constraints and goals for the architectural problem at hand. The design solutions will go through an iterative process of refinement and development. The iterative process will stop once the solution satisfies project goals and constraints (Gagne, 2011). This process can be described as the conventional, or non-computational, approach to design optimization. As mentioned above, architecture is about *forms* and *functions* of buildings, and how to establish a relationship between the two (Mitchell,

1990). The relation between form and function is bidirectional, but due to architects' affection with artistic sensibility, aesthetics, and intuition, a greater emphasis is perhaps placed on form. The above process—though it may utilize computer simulations to measure performance—is non-computational in the way in which it effects the form and optimizes the design solution. The problem with this type of approach is the inability of non-computational methods to accommodate transcendence of architectural creativity beyond the sphere of human understanding and interpretation (Terzidis, 2006). In contrast, computationally generated forms are about the process of exploration and can be considered an extension of the human mind, or even as a dialog between the human architect and the computational agent.

In conventional methods, the exploration of design space is based on the manipulation of design variables, experience, rules of thumb, and comparisons with benchmarks (Reinhart, 2014; Wang et al., 2005). It is difficult for a designer to develop intuition to anticipate the effect of parametric change on the overall performance (Reinhart, 2014). For example, covering a façade with glass curtain panels will allow more daylight to enter the building but may simultaneously lead to unintended increase in thermal loads.

The interaction between human-made and natural ecological systems that may affect the performance of the built environment is complex (Caldas & Norford, 2002). In the first volume of the *Daylighting Handbook*, Reinhart (2014) promotes an evidence-based approach towards better performance-based architectural design, referred to as the “DIVA” approach. DIVA is an abbreviation for *design, iterate, validate* and *adapt*. The principle of DIVA is that an educated design decision is a better design decision and that a series of “better” decisions will result in an overall optimized design. The DIVA approach consists of the following steps:

1. Formulate a list of project goals, i.e., priorities, which correspond to performance requirements.
2. Conduct design iterations to explore different ideas.

3. Evaluate design iterations based on the prioritized performance metrics from the first step.
4. Adjust designs to meet the prioritized metrics.

This process may be carried out manually. However, as mentioned earlier, manual processes may limit the creativity of the designer and significantly diminish the search space (Terzidis, 2006). The greatest potential, therefore, lies in computational design evaluation methods to facilitate and support informed design decision making (Mahdavi & El-Bellahy, 2005). Affordable computing power and extendable CAD and BIM systems made it increasingly possible to use simulations to understand the factors involved in performance optimization (Reinhart, 2014).

The two most common computational methods that resolve conflicting multi-objective criteria: 1) A traditional composite objective function using a weighted sum (Yan et al., 2015); 2) A multi-objective search for the Pareto-Optimal set (Radford & Gero, 1988).

The weighted sum method combines the multiple criteria into a single criterion on a linear scale. The utility function is determined using weighting factors on each criterion, and normalization of the weighted criterion assessment to allow summation of all assessments. Knowledge of the relationships among the different objectives is needed to determine the weighting factor of each objective (Coley & Schukat, 2002; Fonseca & Fleming, 1993). However, in architectural design optimization, the relationships amongst the objectives are not necessarily known, thus the weighting factors are often arbitrary (Konak, Coit, & Smith, 2006; Rahmani Asl et al., 2015; Yan et al., 2015). Additionally, aesthetic solution space is usually large, complex, and subject to personal and cultural preferences and therefore is difficult to include in optimization processes (Coley & Winters, 1997). It is not always possible to find a single optimal solution for a multi-objective optimization problem (Rahmani Asl et al., 2015).

An alternative to the weighted sum method overcomes some of these problems. The multi-objective search for the solution to the optimization problem is a family of possible optimized results known as the Pareto-optimal set (Fonseca & Fleming, 1993).

A Pareto Improvement is when a change in a parameter improves an objective without degrading other objectives, while a Pareto optimal design solution is one that does not possess the possibility for further Pareto Improvements (Radford & Gero, 1988). A Pareto-optimal set consists of all the Pareto optimal design solutions.

By integrating a Pareto Optimality method in the design selection, one may arrive at a set of objective-based design solutions that can be presented to reviewers. For example, one may conduct a multi-objective optimization for various quantifiable performance mandates, such as the ones categorized by Rush (1985), to compute a family of Pareto Optimal design solutions. Nevertheless, this process may only optimize the quantifiable performance mandates such as daylighting and energy use. Non-quantifiable objectives, e.g., aesthetics and artistic self-expression, will require the designer's input and may need additional algorithms to arrive at a formally diverse set of solutions (Yan et al., 2015). The optimal family of solutions and their corresponding performances can be available to evaluate where there can be multiple design solutions, each of which meets the following condition: any improvement of one objective will negatively impact at least one other objective (Altabtabai and Yan, 2015). Because all the presented designs are optimal, the design review may focus on assessing criteria that are not objective or not quantitative.

2.6. Software Tools for Supporting Design Review

Virtual reality (VR) in the context of the following review is the experiential digital visualization of three-dimensional content in real-time, i.e., interactive walk-through. Although this research is concerned with design reviews in academic settings, lots of significant and relevant research have been done in the professional practice. Examples of integrated CAD or BIM models with VR or game engine in professional practice and academic settings are both examined. Because of the multi-faceted and rather complex possibilities for categorization, the literature is presented chronologically rather than categorically.

For professional practice, Fu and William (1999) developed a Web-enabled design review software for professional practice called *virtual design review*. The software

allows multiple reviewers to evaluate an architectural design in real-time using a web browser to navigate a Virtual Reality Modeling Language (VRML) file. The 3D model is accompanied with a floor plan, which is used to show each reviewers' location in the model and other textual information (Fu & East, 1999).

Fröst and Warren (2000) discussed a collaborative design process in which VR, in comparison to conventional design methods using paper and pencils, was found to have helped the users by enabling them to better formulate, test, analyze, and finally realize their ideas. VR provided the common ground between the communicator and the recipient of a design idea to eliminate the possibility of misinterpretation to some extent. Design decisions in VR were more informative than ones made during conventional design reviews. During conventional design review methods, a great deal of the presentation time is spent on clarifying complex spatial qualities in the plans, sections, and elevations. In this research, reviewers were more focused on questions such as measures and sight lines when using VR. In VR, designers and reviewers are not constrained by the abstraction of projective drawings. Rather, they can interrogate the design from different unscripted point of views. This transparency and freedom of design inquiry facilitates better reviewer comprehension of a project; therefore, a reviewer may provide a better and informed feedback to the designer (Fröst & Warrén, 2000).

Campbell (2000), investigated the use of VRML and the World Wide Web as a substitute for construction documents by constructing a prototype and testing it in the design and construction industries. The prototype disseminates design documents as VRML design option models and textual data as HTML to the client, contractor, and fabricators. In this study, hyperlinks and multiple representations of a design project have been found valuable to facilitate better a comprehension of design projects. The use of VRML models was perceived useful by the client, contractor, and fabricators, specifically: VRML's ability to support varying level-of-detail at multiple scales; lesser need to print multiple views of the same model; checking for construction and lay-out conflicts; the linkage between VRML graphical information and HTML textual

construction specifications. Central to the finding is the acknowledgment of the need for different types of representations, not only 3D models, to assist in spatial relationships and analysis. The display of context-sensitive information when needed was also suggested (Campbell, 2000).

Fröst et al. (2001) explored the possibilities of using game engines in design studios for architectural design to communicate spatial information, moods, and feelings. The inclusion of atmospheric light, sound, and juxtaposition between 2D and VR visualization were useful (Fröst, Johansson, & Warrén, 2001). Fröst (2002) developed a working prototype of an interactive design tool for participatory design environments using 3D modeling and other VR tools. It was observed that the immersive quality of VR is useful when evaluating design proposals where it promotes spontaneous discussions around spatial qualities as if walking through a real building. A birds-eye view was noted to be very useful to grasp the conceptual totality of the design solution (Fröst, 2002).

Yoon et al. (2004) discussed the advantages, disadvantages, and comparison of VR in QUAKE II game engine and Web 3D software for the creation of interactive architectural representations. The paper cited the following as requirements for interactive representation: real-time walk-through; interaction with objects & materials; environmental effects; 3D sound; multi-user or avatar interaction (Yoon et al., 2004).

Roberts (2004) did a comparative study where students work was presented in both slideshow and pin-up formats. The slideshow was accompanied by a second screen where Naviswork was used for a walk-through. The walk-through window was accompanied with a plan and a section that update according to the user's location in the model (Roberts, 2004).

Moloney and Lawrence (2004) explored the application of Collaborative Virtual Environment (CVE). The prototype for this study was based on a game engine to support the early stages of design in the context of architectural education. The study utilized CVE as a means to research design context in a manner that is not possible when using standard architectural visualization software. The outcome of the study suggests that

inspecting design iterations in a real-time environment and incorporating 3D sound to evoke occupancy and materiality are important (Moloney & Harvey, 2004).

Johansson and Roupe (2005) presented a framework for importing BIM models into a VE. Their prototype permitted real-time editing of terrains and roads using two-dimensional colored texture masks (Johansson & Roupé, 2005).

Niemeijer and Vries explored the technical feasibility of a constraint-based mass-customization system for housing projects. The system uses multiple windows for textual and non-experiential graphical representations of design options for housing developments (Niemeijer & de Vries, 2007). One of the representations was interactive, which allowed for the rotation of an isometric camera around a geometric model. Price (2008) explored the possibility of inserting PowerPoint presentation slides in spatial virtual environments using a game engine (Price, 2008). Pauwels et al. (2010) created a test case to illustrate how game engines and architectural semantic can be combined to enhance information visualization for architectural design and construction. Shen and Kawakami developed a VRML-based tool to attain consensus on townscape design where different, but non-formal façade design alternatives may be selected (Shen & Kawakami, 2010).

A more recent study of utilizing game engines was conducted by Yan et al., (2010). The study used Microsoft XNA as a game engine and Autodesk Revit as a BIM authoring tool. The outcome of this linkage enabled users to interrogate the VE freely. It allowed for an intuitive exploration and evaluation of the design before it was built. The system also made use of a BIM database where the properties and parameters of specific linkage between spaces may be used for navigation in the game environment (Yan et al., 2011).

For professional practice design review purposes, Kumar et al. (2010) developed an interface for experience-based design review for health facilities. In this research, the author developed a tool utilizing a game engine for a user scenario-based design review. Although BIM was used in this study, it was only a modeling platform; therefore, none of the parametric qualities or parameters of the model were carried over to the design

review tool (Kumar et al., 2011). Similarly, Bullinger et al. (2010) developed an instrument for real-time inspection and annotation of non-BIM, non-parametric architectural virtual models for *participatory design* process (Bullinger, Bauer, Wenzel, & Blach, 2010). The method allows for spatial visualization of thermal airflow simulation results in the VE.

Shiratuddin and Thabet (2011) explored ideas of a design review interface for non-parametric models. Although the system allowed for the association of some parameters to objects within the VE, it did not integrate a BIM authoring platform (Shiratuddin & Thabet, 2011). Moloney and Dave (2011) developed a Web-based tool that takes advantages of multiple representations, e.g., animation, graphs, and interactive walk-through mode, to evaluate design options for a sun screen. The study confirmed the perceived beneficial use of multiple representation methods to qualitatively and quantitatively assess non-formally disparate design options. The study was done to take advantage of non-BIM based models, such as Rhino, Maya, and Sketchup, i.e., no BIM data were included. Additionally, the study did not make use of any orthographic drawings, e.g., plans, sections, and elevations (Moloney & Dave, 2011).

Bahar et al. (2013) discussed a method to visualize building performance data, specifically thermal simulation results in immersive virtual environments. The prototype used a BIM model for the geometric description and an IFC model for performance analysis. The geometric model and the results of the performance analysis are then combined using a game engine (Bahar, Landrieu, P ere, & Nicolle, 2013). Oerter et al. (2013), developed a software system for professional practice that couples BIM and a game engine for evaluating interior furniture layouts. The objective of this research is the creation of a virtual modeling environment, where architects may present building concepts and design options to clients. The proposed tool would allow for the exchange of data between BIM and virtual environments (Oerter et al., 2013).

In the category of serious games, Moloney (2017) recently developed an architectural serious game for Integral Sustainable Design (ISD), where there is equal emphasis on qualitative and quantitative performance (DeKay, 2012). Serious games are

ones that are explicitly designed for educational purposes (Abt, 1970). The game provides non-realistic, geometrically simple real-time design options of a rectangular box along with non-scientific performance feedback, but based on rule-of-thumb design decisions. Qualitative feedback is provided via first-person views of the model, and quantitative feedback is provided via graph-like dials. Design options are based on orientation (rotation) of the building and window placement (Moloney, Globa, Wang, & Roetzel, 2017).

The limitations of the various research examples stem from one or more of the following: the confinement of screen space to a single desktop display and mobile platforms such as laptops and tablets; the lack of performance based visualization within the interactive VE; the lack of an interface for viewing object parametric properties and; the lack of formally disparate design options that are enabled by parametric modeling.

Implementations and prototypes of research projects, such as the mentioned above, are not necessarily accessible to the general body of academia and architectural design industry. There are also commercial software products marketed as design review tools for parametric models. For example, Keough et al. (2009) developed a now discontinued mobile application for collaboration through BIM model viewing, markup, and data-query. A now discontinued Autodesk Showcase® was a design review tool that allows for animation and interactive walk-throughs. BIMx® is a desktop and mobile platform for the exploration of Archicad® BIM models with game-like navigation for presentations and construction coordination. Lumion3D® is a real-time rendering engine that can export still images and choreographed walk-throughs. Similarly, LumenRT® is another platform that allows for a live walk-through mode with the ability to display limited BIM information if available. Enscape® is a real-time rendering plugin for Revit which enables walk-through and fly-through modes for Revit. The plugin allows for interactivity within the Revit software environment or as a standalone shareable program. The software also supports real-time acoustic sound simulation. More recently Autodesk released Revit Live®, cloud-based software for walk-through evaluation of Revit models. Models may be further manipulated via the Stingray game engine, to be

experientially explored via desktop, mobile, or head mounted displays (HMD). Revit Live provides access to object parameters, and incorporates animated objects, dynamic lighting, and different rendering styles.

The limitations of these software tools stem from their simplified system interfaces that prevents customization, lack of support for design options, lack of inclusion of parametric properties or modification of designs using parameters, and absence of visualization of performance. Most of these software tools restrict the interaction with the model to a single viewport, preventing the simultaneous experience of orthographic drawings and perspective views. Therefore, the designer is constrained by the pre-configured software package that requires switching between different points of view to gain total comprehension of spatial qualities and switching among the various user interfaces to display the parametric information and performance-based visualizations.

Of course, there exist other software tools that are marketed as design review tools or may be appropriated as such. However, reporting a comprehensive list of software tools that may aid design reviews is outside of the scope of my research. As it stands, no single tool contains all the features and specifications required to conduct a parametric design review.

2.7. Theoretical Specifications of PDR

The materialization of computational thinking through digital technologies in architecture marks a paradigm shift in the nature of design media, representation, and design tools. Dave (2000) explains this shift in three relevant points: 1) Unlike traditional design media, digital representations contain computable structure even if used solely for display; 2) Unlike traditional representation where order of design operations is free, the underlying framework of digital representations may only be manipulated in a particular sequence, i.e., algorithmically; 3) The multitude of digital media types, e.g., animations, renderings, audio, is challenging if not impossible to achieve using traditional media (Dave, 2000).

In general, digital representations contain a multitude of data and information layers. At face value, digital representations may seem to provide the same one-dimensional set

of information as traditional media (Dave, 2000). Conventionally, screens and projections show limited information at a time, but the more we explore, the more we may discover the endless world of information behind the screen (Engeli, 2000). Marcos Novak envisioned a continuously unfolding computational design space that give rise to dynamic architecture through *hypersurface* and *hyperspace*. A hypersurface is the 3-dimensional projection, i.e., representation, of the 4-dimensional hyperspace, i.e., information space. Novak argues that the screen is a hypersurface, where virtual spaces are represented through the continuous change of information (Imperiale, 2000). Similarly, Engeli (2000) discusses the term *hyperdocument*. A hyperdocument is a conceptual model of an *information space* that allows rich, multidimensional information structures to be built. In a hyperdocument, one may travel along various paths and explore relations in different views. Every bit of information in a hyperdocument can be accessed in at least one way. Although this information space is multidimensional, it is reduced to two dimensions when projected on a screen. Information space is where one may find knowledge and answers through accessible information. “The most intriguing way of using the information” states Engli, “is to create new meaning”. Pelosi (2007) introduced hyper-models, the architectural equivalence of hypersurface and hyperdocuments. The aim of the hyper-model is to enhance the comprehension of construction drawings and specifications through providing markers in the VE that may explain different details using linked orthographic drawings (Pelosi, 2007). Functionalities of the hyper-model as introduced by Pelosi maybe found in commercial software such as AECOSim Building Designer®, a BIM authoring tool, and BIMx®, a design review tool. Using a similar analogy, we may consider BIM models as multidimensional hyperspaces or hyperdocuments, and the associated BIM software interface as the hypersurface where information can be shown, hidden, and manipulated. Note that the multidimensionality referenced here does not relate to time as a controllable factor, rather it is the layering of information, e.g., parameters and numerical values, that may be queried.

BIM-based design methodologies have become ubiquitous in academia and architectural practice (Barison & Santos, 2010). At its core, BIM is a database where 3-dimensional representations of objects are linked to the geometric and non-geometric set of object related parameters. Different objects may contain varying levels of representations that are adaptable to various points of view and/or user preferences. One can easily extract orthographic drawings from a BIM model, and any changes made to the model will automatically be reflected in the drawings. This automatic generation and update of representational drawings allow designers to focus on design problems rather than representational materials. This embedded representational structure in digital media in general, and BIM specifically, affects forms and articulation in design exploration (Dave, 2000). Engeli (2000) argues that when searching for appropriate forms of representations, the following questions are important: “Which aspects should be emphasized? What information should be shown at what point in time? Which dynamics will be useful to explore the information space? What kind of creative interaction will be helpful?”. These are important questions that were considered in the development of PDR. Engeli argues that “Architecture in the digital realm, in addition to providing a space for information, also means creating the views that help to understand the content, structure, and dynamics.”

Conventional design and design review methods do not inherently have access to hyperspaces. For example, as a part of PDR, I suggest the ability to query object parameters in the VE. In traditional design review methods, approximately 83ft² of wall space is needed to expose every object parameter, in a single design option, of a simple single-family-house BIM model. This calculation assumes that every object in the BIM model may have at least twenty parameters. If those parameters were printed to accompany a design solution in a design review, the required square footage would be rather surprising. In conventional digital slide-based design reviews, it is impossible to expose many parameters unless a custom tool is created specifically for parameter query, or through the inclusion of a BIM platform in the design review. Parameter query is only

one example of how PDR may unlock the potential of information layering in hyperspaces.

One of the ways in which the anticipated PDR could facilitate the proposed design review process is by engaging multiple live viewports which may contain geometric, quantitative, and qualitative information. The user interface of PDR could assume that screen space is layered and unlimited, i.e., a hypersurface. PDR could be divided into two broad categories, a main first-person perspective viewport, and a series of, custom, support viewports (Figure 2.2). The main viewport could enable the reviewer to walk-through the model and interact with the VE, while the support viewports may use different, static or dynamic, representations per the designer's needs. This juxtaposition of different representations and information is a strength which used to be exclusively associated with traditional design review methods (Dave, 2000). The multi-viewport approach could be a seminal part of PDR. It may allow for better design inquiry of the form and spatial structure of the environment.

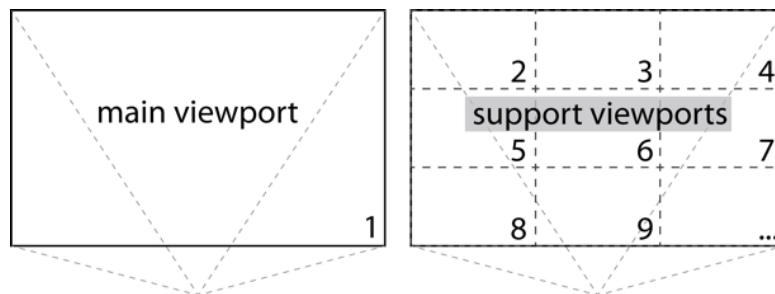


Figure 2.2. Main viewport 1, and customizable support viewports 2-9.

Another example of how PDR could facilitate the proposed design review process is through the inclusion of design options overviews and performance dashboards. PDR could introduce a set of design options selected by the designer. These designs are a set of computationally optimized Pareto Optimal design options. At the beginning of the design review, design options and their corresponding performances can be overviewed. Without delving into the details of each optimized design option, the dashboard could

provide an overall overview of the formal qualities, and a set of performances that contain a comprehensive yet simplified numerical or graphical information of daylight availability, energy, and comfort analysis.

Kalay (2004), uses six points to discuss changing communication and representation in architecture due to the advancement in computer technology. Perhaps a discussion of the six points could more concisely highlight the theoretical specification of PDR. A summary of the points is provided here while a discussion of how PDR addressed these points is included in *Chapter 7*.

Kalay expresses the possibility of changing communication and representation in architecture due to the advancement in computer technology in the following properties of modern computers:

***Flexibility:** the ability to change levels of abstraction as needed without having to reconstruct the representation from scratch.*

***Interlinking:** the ability to link information represented in different ways so that when one representation is modified, the others are too.*

***Information management:** the ability to organize and access complex information resources.*

***Visualization:** the ability to produce photo-realistic images of yet nonexistent artifacts and environments.*

***Intelligence:** the ability to embed design rules, constraints, and goals within the representation itself, making it an active rather than a passive, partner in the design process.*

***Connectivity:** the ability to share information rapidly among all the participants in the design process.*

2.7.1. Flexibility

According to Kalay, one may convert geometric models into a multiplicity of visual representations. Each representation may have a different level of abstraction, e.g., diagrammatic, orthographic, or isometric. Abstraction, according to Kalay, is the removal of information not pertinent to a particular communication and appropriately rendering the remaining information. The total sum of information must be provided by the designer and stored as data. The designer, assisted by computation, may reveal or conceal details from certain communications by displaying only pertinent information appropriate for the desired level of abstraction and graphical conventions. Kalay asserts that seminal to the ability to have different levels of abstraction for various communications is the capacity to switch between them at will. He cites that different communications allow different experts to view a model using different visual conventions suitable for their way of communication. Switching between various levels of abstraction without constructing new representations from scratch reduces errors associated with converting from representation to another.

2.7.2. Interlinking

Kalay describes buildings as complex artifacts that require many representations to be communicable. It is not uncommon to have hundreds of drawings at different levels of abstractions and graphical conventions to comprehensively describe a building from different points of view. The same object might appear in multiple plans and at different scales. If the object is modified or transformed, all drawings that show the object must, therefore, be updated to reflect the change. This ability according to Kalay is of great importance in the design process where modification is a norm until the designer arrives at a satisfactory solution.

2.7.3. Information management

Kalay describes computers as tools for information management with abilities to organize and reorganize the way in which information is linked to assist in given tasks. For example, information and specifications of building objects can be used by the

different parties responsible for the design, manufacturing, and erecting building elements. For BIM models, this information may be stored as object parameters.

2.7.4. Visualization

Architects use visualization of information as a fundamental means of representation. In fact, some may argue that architects do not build buildings but rather only create representations and visualizations (Engeli, 2000). With the advancement of computer graphics, it is now possible to achieve a greater level of realism. Both architects and clients may view a digital model of the proposed building before its realization. According to Kalay, and numerous others, this ability to realistically visualize architecture enable better comprehension of a design solution before committing effort and capital necessary for its realization. Realistic visualization—accompanied with a user interface that makes it possible to view the building in different environmental conditions and using different materials—thus gives rise to opportunities for efficient generation and aesthetic evaluation of design alternatives.

Kalay cites virtual reality technologies as the most important contribution of computational visualization of information. Virtual reality immerses the users in the environment where the building may be experienced from with-in rather than from with-out and therefore evoking the sense of presence. Buildings are meant to be inhabited, and therefore according to Kalay, we may not fully comprehend them using scale models or small images. The use of VR may ameliorate the uncertainty that accompanies conventional scaled architectural representations by allowing the parties concerned to inhabit the environment. The ability to dynamically walk-through the design gives the observer the ability to examine the design from a multitude of vantage points not necessarily dictated by the designer.

“Experiencing a space is a personal and subjective activity” (Engeli, 2000). The same space may have an infinite set of affects due to natural phenomenon such as light, shadow, and sound amongst other sensual aspects. During the design review, it is important to visualize the experiential and sensual qualities of space. As previously discussed, architecture is a bimodal profession (Schön, 1985), and as discussed above,

architects are concerned with *forms* and *functions* of buildings, and how to relate the two. The means of architecture are in the direct interactions of our senses with the architectural environment (Lynch, 2003; Pallasmaa, 2012; Scheer, 2014). Research suggests that critics found it easier to engage with interactive walk-throughs than a pre-prepared animation as it creates a sense of occasion where critics may feel involved (Roberts, 2004).

It is important to note that my research is not concerned with dictating or specifying which representation or visualization methods are more effective to conduct a design review. Rather, this research aims to provide extreme case samples of dynamic representations from amongst the infinite spectrum of possible digital representation methods. The author accepts the axiom that representation and level of abstraction specificity are directly affected by how a designer may wish to communicate design intent (Kalay, 2004).

2.7.5. Intelligence

According to Kalay, rules, constraints, and goals within representations of objects make them active in the design process. For example, embedded parameters and constraints control the permissibility of design solutions. This level of intelligence may save the designer from making humanly undetected errors and may speed the possibility of modification. According to Kalay, this embedded intelligence can be effective without being elaborate where simple rules may make the model effectively evolve due to change. Complex constraints and parameters may even propose valid alternative design solutions.

2.7.6. Connectivity

Computer-aided representation, according to Kalay, may benefit from the ability to electronically share information. It allows for rapid feedback from concerned parties with regard to proposed design solutions, test the solutions feasibility, and include more experts in the design process in a shorter amount of time than traditional communication methods. The importance of such connectivity and collaboration becomes more evident

with the increase of design complexity. Additionally, a modern project may require global connectivity as architects, clients, and consultants may collaborate even if geographically disconnected. Such is the case for professional practice where there is a need to broadcast design review sessions amongst different participants.

2.8. Feature Specifications of PDR

The above discussion provides a theoretical framework of PDR. The following is a conclusive feature specifications list to be implemented for PDR. A discussion of the feature specifications mentioned below and, to some extent, their implementation process can be found in Chapter 5. A tool for design review of parametric BIM models should support the following feature specifications:

- a. Multiple viewports that automatically update
- b. Integrated performance-based analysis
- c. Multiple design options
- d. Animated design options morphology
- e. Real-time section drawings
- f. Multiple visualization methods
- g. Dashboard evaluation method
- h. Mapping of analysis results onto surfaces in the 3D environment
- i. Pareto optimum design options selection process
- j. Multi-objective optimization simulation results
- k. Different levels of abstraction for representations
- l. User proximity indication and user location awareness in representations
- m. Access to objects' BIM parameters
- n. Exposure of parametric framework
- o. Multiple points of view of the model
- p. Navigational evaluation method
- q. Integrated performance-based analysis in the navigation evaluation method

- r. Contextual information
- s. Dynamic sun and sky system
- t. Vegetation
- u. Sound simulation
- v. Wind simulation
- w. Integration of multiple displays

Note that the listed features may be implemented in many different development environments. However, game engines' development environments are pre-equipped with tools and modules that facilitate the implementation of the mentioned feature specifications.

2.9. Summary

This chapter provided a literature review on design reviews, parametric modeling, BIM, game engines, performance-based design, multi-objective optimization, and software tools for supporting design review as the presented research is built on top of these technologies and studies. Limitations of paper-based and slide-based design reviews constrain the potentials of parametric and BIM models. Parametric BIM models are usually presented, and therefore perceived, as static finalized models. Additionally, the advantage of having a parametric model which may generate multiple design options is neglected in the review process (Krish, 2011). Collectively, parametric and parametric-BIM modeling software lack functionalities for comprehensive design presentation and evaluation (Altabtabai & Yan, 2015; Scheer, 2014).

To gain a thorough understanding of parametric and parametric BIM-based design projects, a new user interface –one that allows for qualitative and quantitative design evaluation– is necessary for architectural design reviews and presentations. Because the possibilities for interaction in a virtual game world are vast, this research aims to address limitations of current design review methods by using a game engine, as a development environment, to facilitate comprehensive communication of multiple design options. By integrating a Pareto Optimality method in the design options' selection, one may arrive at a set of objective-based design solutions that can be presented during design review.

Finally, the discussion provides a theoretical background about conventional—traditional, digital, and hybrid—design review methods and PDR. PDR can be seen as a hypersurface. It provides an interface through which one may interact with, access, reveal, conceal, and manipulate information in hyperspaces. Additionally, theoretical as well as possible feature specifications of PDR were provided. This quote from Engeli (2000) is an appropriate manner to conclude this chapter and to summarize the research intent:

To tackle new challenges, to explore new possibilities and to step beyond what is currently possible and acceptable in architectural practice are prerequisites in the search for answers to the question: How can architecture be revealed on a screen?

3. METHODOLOGY

The study was conducted in three phases. Phase 1 was conducted as a comprehensive literature review of existing methods and technologies for BIM-based design review and presentations and resulted in identification of limitations of current methods and a specification of the performance of a software tool that can better support design reviews. Phase 2 involved the development of a prototype interface that can address the limitations of current methods and improve design review by meeting the specifications of performance. Phase 3 utilized multiple focus group discussions where the prototype developed in Phase 2 was demonstrated to produce qualitative assessments to establish effectiveness of the prototype and validity of results. Together these phases produce evidence regarding how software can be used to improve the design review process. A description of each phase is provided below.

3.1. Phase 1: Literature Review

The literature review was continuous throughout all research phases to constantly identify the most recent relevant studies. The focus of the literature review was on design review methods using digital tools. Limitations and advantages of existing methods for design reviews were highlighted. A list of criteria was used to identify the gap and the limitations of existing methods. Therefore, the literature was analyzed for the following criteria:

- **BIM-based versus CAD-based:** did the study utilize BIM or CAD models? For example, special consideration was made to ensure that BIM models were not used *solely* for the comprehensive geometric definition of BIM elements. If the study only used the geometric data from BIM, then it was categorized as a CAD-based approach.
 - **Parameters:** if the study utilized a BIM model, did it include objects' parameters, or was it a method to explicitly demonstrate the parametric framework?

- **Walk-through:** did the study provide a method to freely navigate through the design project?
- **Design options:** did the study include multiple design options? If so, are the design options formally disparate?
- **Performance-based visualization:** did the study include performance-based visualization as a part of the design review method?
- **Multiple viewports:** did the study use multiple viewports to communicate design? If so, did it include any of the following:
 - Floor plans drawings
 - Section drawings
 - Still renderings
 - Mini-map
 - Parameter viewers, i.e., a way to report object parameters
- **Game engine vs VR:** did the study utilize a game engine or other means to develop a proposed method?
- **Optimization:** did the study consider optimization as a part of the proposed framework for generating multiple design solutions?

The above criteria helped shape PDR and suggested the included functionality and establish research originality.

3.2. Phase 2: Prototype Development

Development of a prototype establishes that the specifications for the tool are complete and also produces the apparatus by which empirical evidence may be gathered. This phase consists of three subparts. Phase 2.1 involved: the selection of a test case architectural design project that may be used to demonstrate the proposed method; the creation of a parametric framework, conducting performance-based simulation, and generating a Pareto optimal set of design solutions for the test case project; and finally the description of the test case variations and each of their performance data was prepared for incorporation into the game engine. Phase 2.2 involved the development of

the working prototype using a game engine by incorporating the materials developed in the previous steps of this phase. The following is a description of each sub-phase of the prototype development.

3.2.1. Phase 2.1: test case selection and preparation

Upon inspecting multiple published architectural projects, the choice was made to use the House for Trees (HFT), a project designed by Vo Trong Nghia (VTN) Architects. HFT is an environmentally-conscious built project that consists of five concrete *boxes* that act as pots for roof gardens and trees (VTN Architects, 2014). The following factors were foreseen as advantageous if the HFT is adapted for this test case:

- HFT is a small-scale project which may be computationally more efficient for preparing tests than a larger project.
- HFT is an architectural project that is difficult to communicate using only abstract orthographic visualization and representation methods. To comprehensively understand the design intent, experiential and phenomenological qualities, such as vegetation and wind, need to be communicated.
- The rich material characteristics of the HFT that affect the experiential assessment of the project—specifically the exterior concrete wall corrugations and texture—are not ones that may be easily communicated using BIM built-in default rendering and walk-through functionalities and thus demand more powerful rendering tools such as those in a game engine.
- The formal organization of the HFT, as a series of discrete volumes, may allow for a representation of morphological variations of design option, i.e., the visual communication of changes amongst design alternatives.

A parametric framework of the HFT test case project was created to allow for the generation of multiple design solutions. The parametric BIM model of the HFT was initially created using Revit® and Dynamo® to generate geometric and non-geometric data.

Geometric data from the BIM model were used as a base for further detailed modeling, environmental performance-based analysis, and to generate optimized design options. An enhanced variation of the BIM geometric model was remade with Rhinoceros® (Rhino) and Grasshopper® (GH) to recreate a parametric framework capable of generating multiple formally disparate valid design solutions.

Non-geometric data were exported from the parametric BIM model. For a design review, not all parametric elements or properties are useful or needed. Therefore, a function was developed to consider only the parametric BIM properties of elements specified by the user.

Two sets of performance-based simulations were conducted with the HFT test case project. The first set was conducted to generate MOO design solutions using solar radiation, privacy, and courtyard size simulations as the optimization criteria. The MOO method was implemented to facilitate the selection of a set of optimized design options from amongst many valid design solutions. By integrating a Pareto optimality method, I arrived at a set of objective-based design solutions from which ten design options were selected. The ten selected design options are the ones to be reviewed using PDR. The second set of performance-based simulations was conducted to the ten selected design options. The simulations were used to report daylighting performance feedback to the user, during the design review, in the form of a dashboard for the ten optimized design options.

A system interface between BIM and gaming was prototyped for transferring design and performance data of multiple MOO design options from Rhino to a game engine, in order to present performance-based design options parametrically. Digital Content Creation (DCC) software, MODO® 10.2v1, was utilized to facilitate the transference of data from the modeling and simulation package to the game engine. MODO was used to create hierarchical relationships amongst modeled elements, alter and optimize geometric data, add geometric details, add furniture and fixtures, apply textures, bake textures into image maps, and export game-engine-ready models.

Two types of data were required for the development of the prototype: geometric and non-geometric data. The geometric data went through a process to make 3-dimensional objects efficient for real-time interactive virtual environments. The process involved the reduction of polygons via remeshing processes and the preservation of details via texture baking. Non-geometric data in the prototype were object parameters and simulation results. These data were either brought to the game engine in their original format, translated into bitmap images, or were converted into geometric data and texture maps via texture baking.

Extensive analysis of as-built drawings, renderings, and photographs was conducted to fully comprehend the HFT. By using published photographs of the finished project, the specific heights of surrounding neighbor buildings were considered and their fenestrations were identified. Details such as light switches, electric outlets, and lighting fixtures were also identified from published photographs, and therefore, were included in the geometric model using MODO.

3.2.2. Phase 2.2: parametric design review user interface prototype

A user interface was prototyped in a game engine (Unity 5.5) to assist in presenting parametric design options and their performances. Once geometric definitions, parameters, and images were stored into the gaming project, it was possible to situate the model, apply textures, define collision properties, and attach different custom behavior scripts to allow for interactivity. The user interface utilized two displays to facilitate the communication and comprehension of architectural design projects during design review. Figure 3.1 is a diagram of the different steps in *Phase 2*.

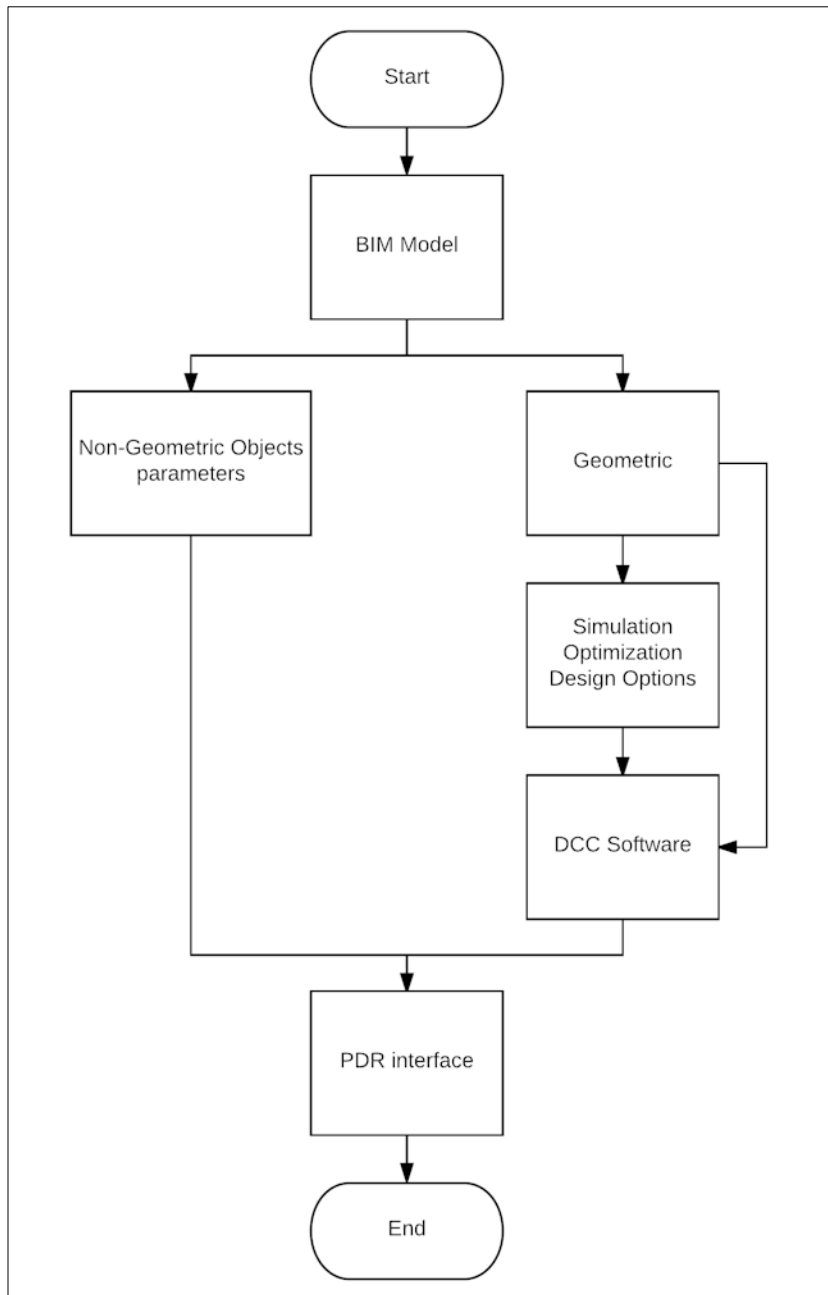


Figure 3.1. Data flow for the proposed system and user interface.

3.3. Phase 3: Focus Group Experiment, Results, and Discussion

For the validation of PDR, experiments by the author were done with the test case to demonstrate the functionalities and usefulness of PDR. Focus group interviews were

conducted for qualitative evaluation of PDR and further discussions. Focus groups were carried out to evaluate the *perceived usefulness* and *theory confirmation* of PDR. Davis (1989), suggests the *perceived usefulness* construct as a way to determine a system's usefulness. Fern (2001), sees that focus groups may be used as a stand-alone method to *confirm* theoretical notions directly.

Focus groups are guided semi-structured groups conducting discussions on a selected topic, e.g., market research, political analysis, and evaluation research (Dawson, 2002; Ruane, 2005). The author participated in the focus group as a moderator. Participants of the focus group fit into the following categories: (a) design studio instructors or faculty members; (b) design studio instructors who may professionally practice architecture and use digital design and modeling tools; (c) graduate level students who use digital design tools; and (d) undergraduate students who use digital design tools. Focus group discussions were video-recorded for detailed analysis of the interview sessions. Criticism and comments from the focus group were used to validate the method. Additionally, further modifications were suggested in this dissertation for future improvement of the system.

Davis (1989) extensively discusses the constructs of *perceived usefulness* and *perceived ease of use*. According to Davis, two determinants are important that may influence a system's use. First, people base their decision to the extent they believe the application will help them perform their job better. Davis refers to this variable as *perceived usefulness*. Second, even if the potential users find a particular application useful, they may, at the same time, believe that the system is too hard to use and its benefits may not outweigh the efforts of using the application. Davis refers to this second variable as *perceived ease of use*. Because there are no current plans to spread the prototype beyond the scope of this research, the *perceived ease of use* will not play a major factor in the validation process, and therefore, I will aim only to measure the *perceived usefulness* of the method. Davis (1989) defines perceived usefulness as "the degree to which a person believes that using a particular system would enhance his or her job performance". The definition of the word *useful* is: "capable of being used

advantageously” (Davis, 1989). A system which scores high in perceived usefulness is one that, through which, users believe will positively impact their performance.

For focus group research methodology purposes, the proposed research fits into the category of *experiential focus group tasks*. Fern (2001) partitions *experiential focus group tasks* into *theoretical* and *applied* tasks. The word *experiential* here refers to the thoughts, feelings, behaviors shared by members that fit in the same group. For *theory* applications, experiential focus groups are utilized in two ways: *triangulation* and *confirmation*. For evaluation purposes, focus groups may be used as a stand-alone method to *confirm* theoretical notions directly. According to Fern (2001), theory confirmation is the comparing of information gathered from focus groups with the researcher’s prior beliefs. Fern also suggests that significance of the experiential use of focus groups lies in knowing that each focus group respondent speaks for him/herself as well as for the primary groups with which he/she shares common knowledge.

Examples of the use of focus groups to validate theoretical constructs or evaluate and improve tools are abundant. For example, Jeong and Lambert (2001) conducted a focus group of nine faculty and staff members from a large university. The study aimed to identify attributes that make a high-quality website, to define the concepts of perceived usefulness, perceived ease of use, and accessibility, and to clarify how to discriminate two different levels of each construct. Liu et al. (2007) held a focus group, after seven participants interacted with an augmented reality system, to discuss the participants’ *perceived usefulness* and *perceived ease of use* of the system. Kim and Forsythe (2007) conducted focus group interview with 11 undergraduate students to gain insights regarding their attitudes towards usage of virtualization technologies in apparel shopping process, specifically about the students’ perception of the system. Some of the mentioned research examples used other methods in addition to focus groups to further refine *construct-measuring instruments*, to further research through triangulation, or to verify hypotheses.

For this study, focus group discussions were conducted where all participants were associated with Texas A&M college of architecture. In total, four focus groups were

conducted. Focus Group I and II were conducted with faculty members. Focus Group III was conducted with graduate students. Focus Group IV was conducted with undergraduate students. All focus group sessions were conducted between March and April of 2017.

All sessions were video-recorded and transcribed for analysis. Analysis of the focus group discussions involved categorizing and organizing responses into several constructs. The categories were generated from the research problems, feature specifications of PDR, or emerged from the focus group discussions. Responses were compared and contrasted for similarities and differences. The main construct in this study tests for the *perceived usefulness* of PDR.

3.4. Summary

The literature review and limitation of existing tools have led to the development of the proposed method. The proposed method necessitated a test case project for the demonstration of PDR. A parametric framework for the test case project was created to allow for the generation of multiple yet valid design solutions. A MOO method was implemented to facilitate the selection of ten optimized design options from amongst the Parato Optimal design solutions. The optimized design options and their associated performances, including geometric and non-geometric data, were processed for use in a game engine to create the apparatus for demonstrating the PDR interface. Experiments were conducted with the test case to demonstrate the usefulness of the PDR interface and to validate it. The demonstration took place in a series of focus group sessions with participants sampled from populations that would directly benefit from the new method. Focus group sessions were utilized to measure the *perceived usefulness* qualitatively, and as a validation method through *theory confirmation* (Davis, 1989; Fern, 2001).

4. TEST CASE SELECTION AND PREPARATION

A test case was developed to produce qualitative assessment of PDR's theoretical and feature specifications. A parametric framework of the test case building was created to allow for alternate design solutions. By integrating a Pareto Optimality method in the filtering and selection of design options, we arrived at a set of objective-based design solutions. Ten design options were selected from amongst the Pareto front solutions. The ten selected design options are ones to be used for assessment and validation of PDR.

4.1. Test Case: The House for Trees (HFT)

Upon inspecting different published buildings, the choice was made to use the House for Trees (HFT), a project designed by Vo Trong Nghia (VTN) Architects (Figure 4.1). The choice of the HFT may become clearer towards the middle of this chapter. Nevertheless, the following are factors that were foreseen as advantageous if the HFT was adapted for this test case.



Figure 4.1. House for Trees. Photograph provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).

First, the HFT is a small-scale project which may be computationally more efficient for MOO methods. Second, the house is an excellent example of architectural projects that may not be communicated using only abstract projective representation. To comprehensively understand the design intent, experiential and phenomenological qualities, such as vegetation and wind, need to be communicated. Third, while the massing of the HFT is simple, the textural qualities of the surfaces—specifically the exterior concrete wall corrugations and texture—are not ones that may be easily communicated using BIM built-in OpenGL rendering and walk-through functionalities. Fourth, the massing of the HFT may allow for a morphological representation of design option, i.e., the visual communication of changes amongst design alternatives.

The HFT is located in the most populated city in Vietnam, Ho Chi Minh City (VTN Architects, 2014). The city is in the southeastern region of the of the country. The southernmost tip of Ho Chi Minh grants the city access to the South China Sea. According to VTN Architects, the city is subject to overwhelming problem of pollution and an underwhelming 0.25% coverage of greenery. Therefore, the house is an attempt to critique current urban context, as well as an attempt at establishing a much-needed connection between the city and nature (“VTN | Vo Trong Nghia Architects - House for Trees,” n.d.).

Ho Chi Minh City’s climate is characterized by tropical monsoon and high temperatures (wet and hot) with insignificant seasonal variation (Ho Chi Minh City Power Corporation for the Asian Development Bank, 2014). The average temperature is between 26°C - 28°C. The highest recorded temperature is 40°C while the lowest recorded is 13.8° C. The average temperature in the coldest month is above 24°C.

The property onto which the HFT sits is an irregular landlocked piece of land, i.e., surrounded by typical Vietnamese row houses, which can be accessed only via a narrow and long hallway through other surrounding buildings (VTN Architects, 2014).

Figure 4.2 is the site plan of the HFT.

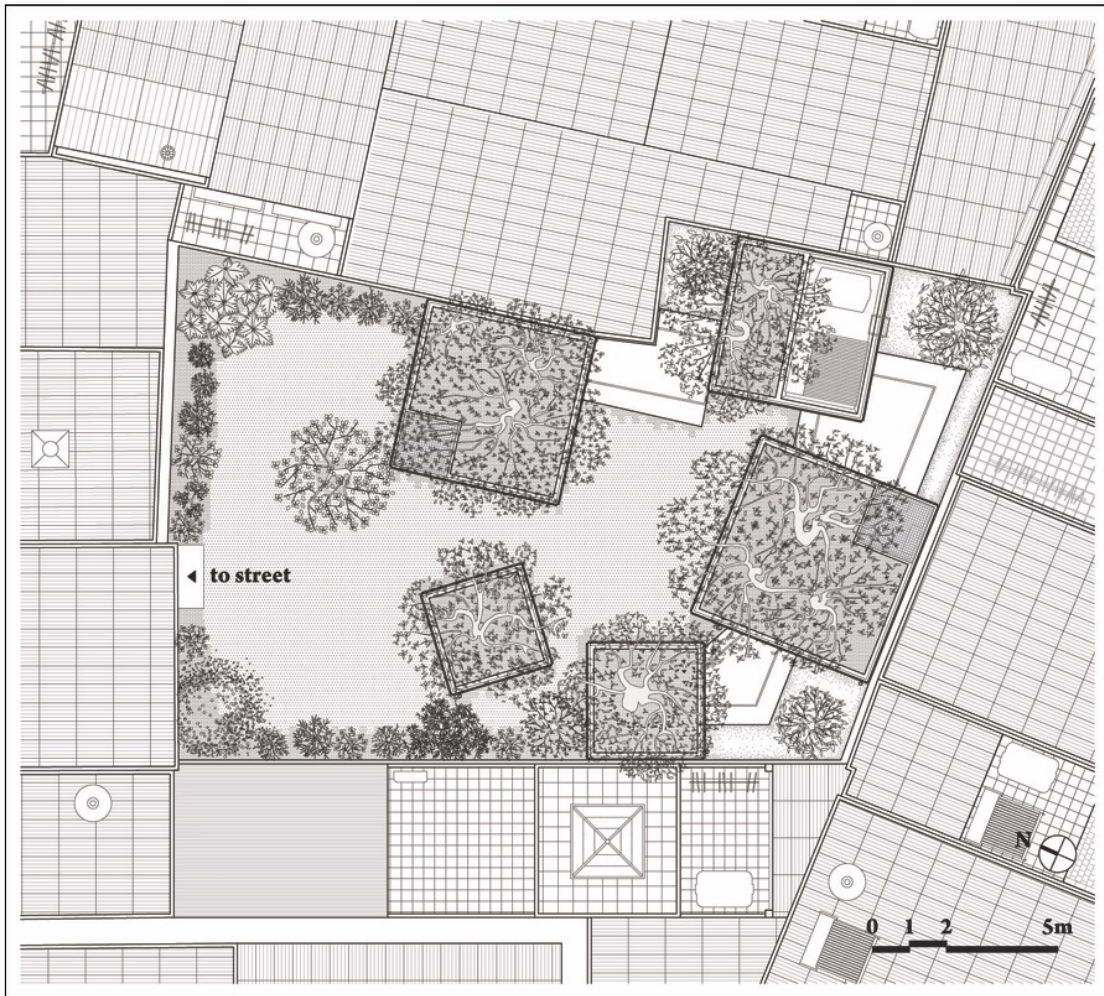


Figure 4.2. Site plan of the HFT showing the landlocked irregular plot. Drawing provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).

HFT can be described as a set five concrete *boxes* that act as pots for roof gardens and trees (VTN Architects, 2014). Going forward, the naming convention of *boxes* will be a suffix number after an italic *box*, i.e., *box01*, *box02*, *box03*...etc. Figure 4.3 shows the spatial location of the five *boxes* and their associated naming convention. As described by the architect, each of the five concrete *boxes*, and their roof gardens, function as storm-water basins for water detention and retention. The *boxes* are arranged to allow for the implicit creation of a central courtyard between them. Operable transparent fenestrations are strategically located and sized for each *box*. Towards the

courtyard, the large glass-panels and aluminum-frame doors and operable windows may provide natural light and ventilation. While windows that may face away from the courtyard are concerned with privacy, and therefore, they are small and located close to the vertical edge of the host wall, or resting the floor (VTN Architects, 2014).

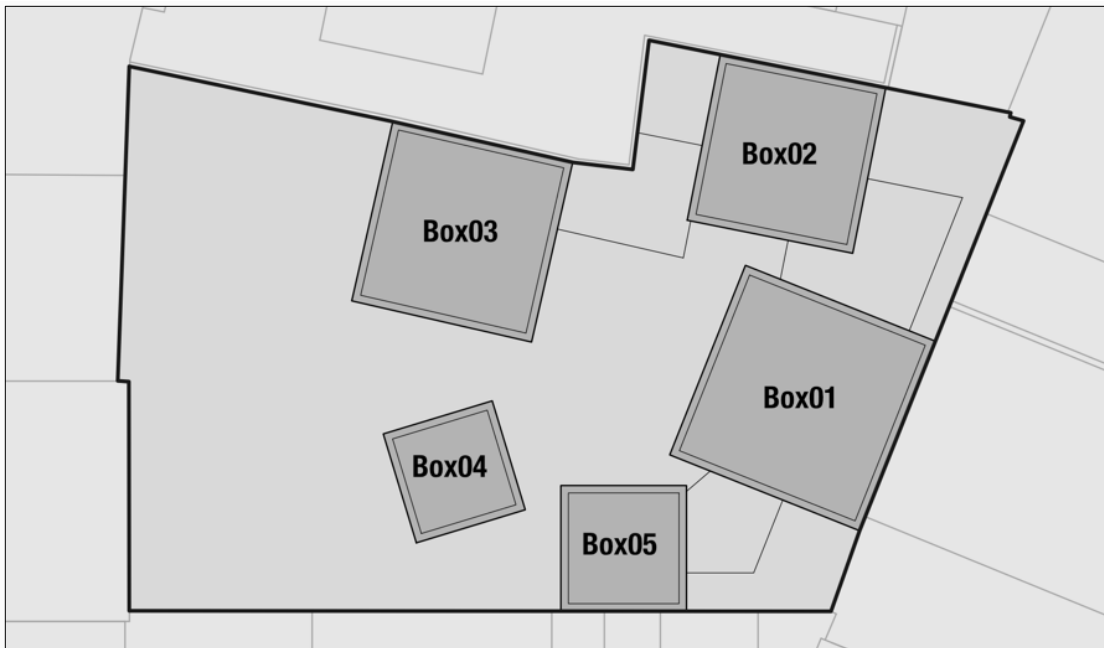


Figure 4.3. The naming convention of the five concrete *boxes* that this research will follow.

Common spaces such as the dining room, kitchen, laundry room, altar room, and library are located on the 1st floor (Figure 4.4). Vertical circulation is housed exclusively in *box02* (Figure 4.5). Upper floors accommodate bedrooms, a bathroom, storage room, and three bridges that connect *boxes 01, 02, 03, and 05* (Figure 4.5). The rooftop gardens and trees help provide shade and privacy to the interior spaces and the central courtyard. Photographs of the HFT also suggest that access is possible to the roof gardens; nevertheless, this quality was abandoned in this study.

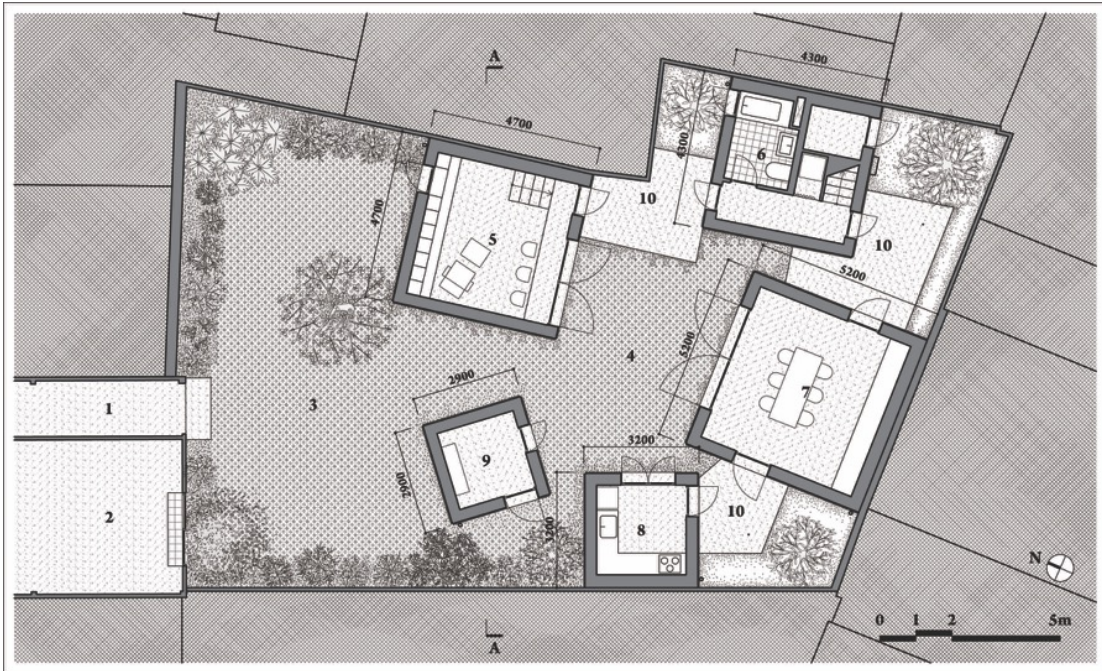
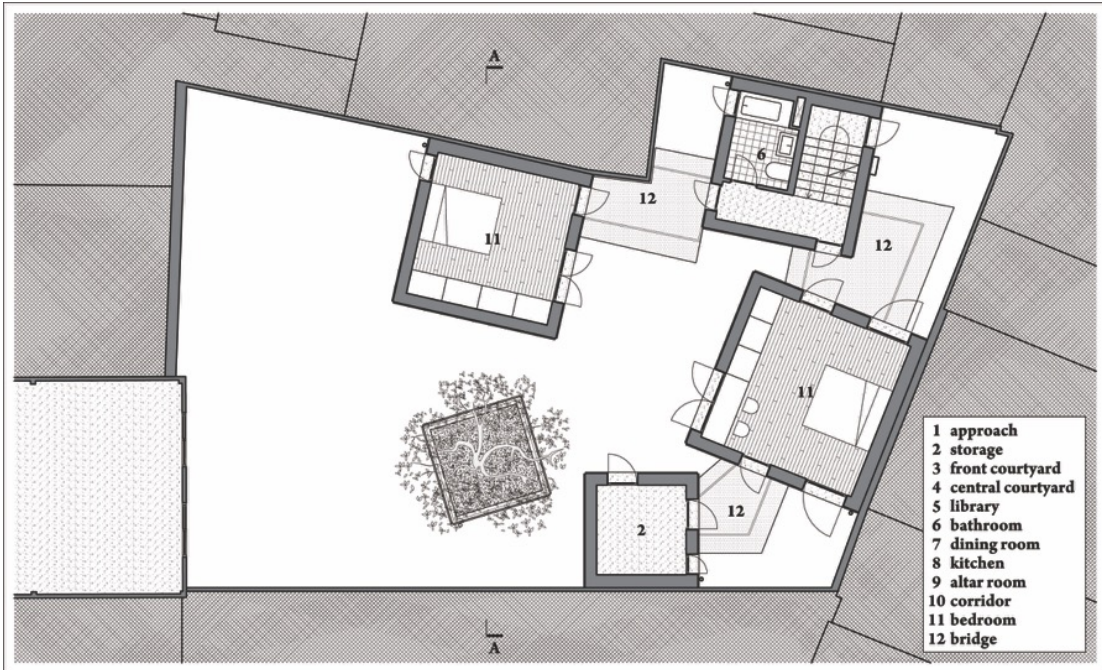


Figure 4.4 First floor plan. Drawing provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).



- 1 approach
- 2 storage
- 3 front courtyard
- 4 central courtyard
- 5 library
- 6 bathroom
- 7 dining room
- 8 kitchen
- 9 altar room
- 10 corridor
- 11 bedroom
- 12 bridge

Figure 4.5 Second floor plan. Drawing provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).

All exterior walls of the HFT are made of poured on site fluted concrete. The flutes in the concrete resemble the bamboo formwork used in the pouring process (Figure 4.6 and Figure 4.7). The kitchen and bathrooms are finished with tiles. All other spaces are finished with bricks (Figure 4.8). Floors finishes may be ceramic tiles, wood, or polished concrete. Corridors connecting the boxes on the 1st floor are made of concrete and bridges on the 2nd floor are made of steel. Lastly, the courtyard flooring is made of grass tile cement bricks (Figure 4.6 and Figure 4.7) (VTN Architects, 2014).



Figure 4.6. Detail of the fluted concrete exterior walls. Photograph provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).



Figure 4.7. Another view of the fluted concrete exterior walls. Also note the use of grass tile cement bricks. Photograph provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).



Figure 4.8. View of the interior space of *box01* looking towards the courtyard, *box03*, and *box04*. Note the use of brick on the interior walls and polish concrete for the floor. Photograph provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).

4.2. Creating Parametric Framework for HFT

Parametric modeling enables generative form-making through the use of definition schemata and constraints (Aish & Woodbury, 2005). A parametric model of the HFT was initially created using a BIM authoring tool Revit, and a visual programming plug-in Dynamo. However, due to lack of documentation, limitations, lack of stability of Dynamo, and limitations of environmental-based analysis tools for Dynamo, the decision was made to reconstruct the same parametric model using Rhinoceros (Rhino) and Grasshopper (GH). The parametric model created using Rhino and Grasshopper closely mimics the way in which the parametric BIM model was created in Revit. Rhino is a NURBS-based geometry model authoring tool that utilizes GH for authoring generative design through visual scripting. By using Rhino and GH, it was possible to overcome all drawbacks noted regarding the use of Revit/Dynamo. Nevertheless, one aspect where Revit is superior to Rhino is that the former is a BIM-based design authoring tool while the latter is not.

In Rhino and GH parametric modeling workflow, one may manipulate parameter values of static instances, i.e., referenced copies, of predefined *independent objects*. An *independent object* is one created using conventional modeling, i.e., has no parametric relationship and/or is not constrained to, or by, other objects. Conventionally, any object created using CAD systems may be considered to be an *independent object*. Manipulating parameter values of non-parametric *independent objects* may give control over the object's transformation matrix, such as translation, scale, or rotation. One may also reference geometry from *independent objects* as a base for a parametric model. For example, a vertex from an *independent object* may be used as the center of a parametric sphere object.

Alternatively, it is possible to algorithmically generate an object using parametric modeling where an element is the outcome of propagation of previous elements. In this research, the HFT parametric framework propagates a model, which references or builds parametric relationships, on top of *independent objects*. Each concrete *box* in the HFT model was considered an *independent object*. Accordingly, manipulating the

transformation matrix of the *boxes* allows for design solutions that are formally disparate.

While it is possible to recreate the whole design of the HFT via the exclusive use of propagation methods, i.e., without relying on instances of *independent objects*, an attempt to do so would be a mere exercise in parametric modeling, i.e., it may not necessarily provide additional contributions to the research. Nevertheless, although the five HFT concrete *boxes* were not generated parametrically from scratch, the steel bridges that connect the *boxes* were parametrically conceived. The parametric model of the simplified steel bridges was observed to successfully adapt to all design alternatives generated throughout this study.

4.2.1. Identifying parameters

The parametric framework controls the five HFT *boxes* to manipulate their location and/or rotation. Two variable transformation parameters are used for each of the five *boxes*: a position parameter and a rotation parameter. The framework varies these parameters to generate different design solutions, then evaluates each design solution using MOO. Note that the use of MOO does not dictate the number or type of parameters used in this research. Rather, MOO, in this case, is utilized to arrive at a set of design options that are based on performance trade-offs, rather than arbitrary designer preferred solutions. For each *box* in the HFT, there are multiple *independent objects* of different model elements. These objects may be points, curves, polygonal mesh, or Boundary Representation (Breps). For each *box*, all associated *independent objects* are encapsulated so that they may inherit transformations applied to the *box*. Little detail will be reported of each *independent object*, why there are many *independent objects*, or how they contribute to the parametric framework. Rather, only the two most influential ones to the overall parametric framework will be explained in a later section, i.e., *boxPivot* and *boxTrack*. Nevertheless, the following is a list with brief descriptions of all independent objects required for each *box*:

- Point (*boxPivot*): marks the origin or anchor point of each *box* (Figure 4.9).

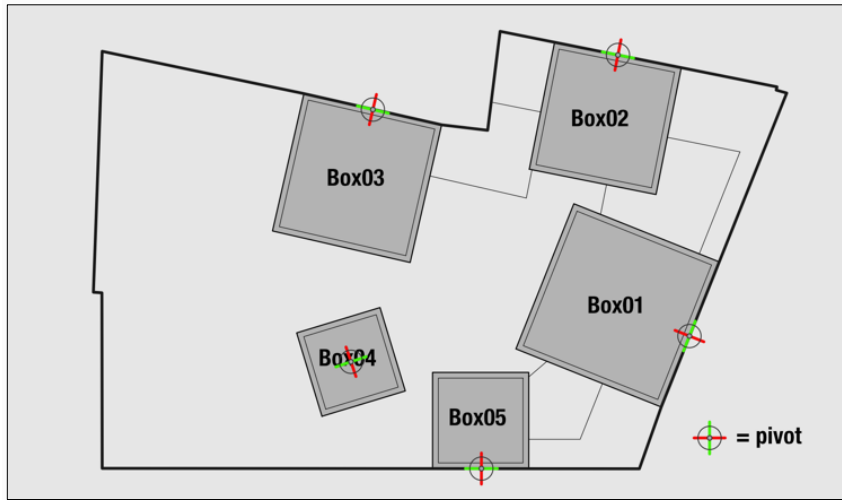


Figure 4.9. the five *boxPivot*(s).

- Curve (*boxTrack*): a track curve on which the *box* may slide along to change position and/or rotation (Figure 4.10).

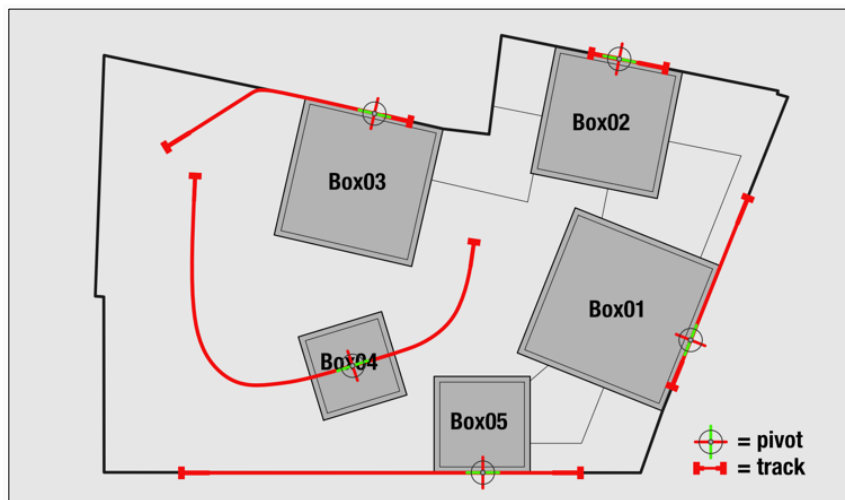


Figure 4.10. the five *boxTrack*(s).

- Curve (*boxOutlineCrv*): a two-dimensional outline curve of the *box* projected on the floor plan (Figure 4.11).

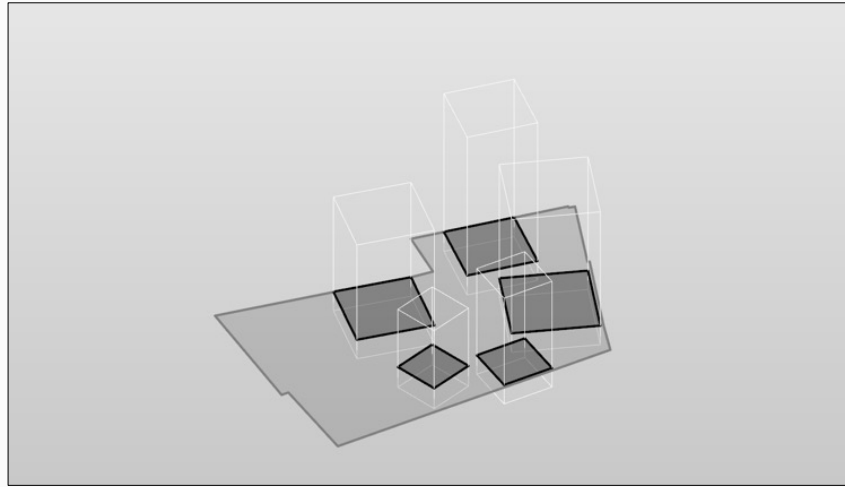


Figure 4.11. *boxOutlineCrv(s)*.

- Brep (*boxComplete*): a detailed geometric massing of the *box* including interior spaces and surfaces (Figure 4.12).

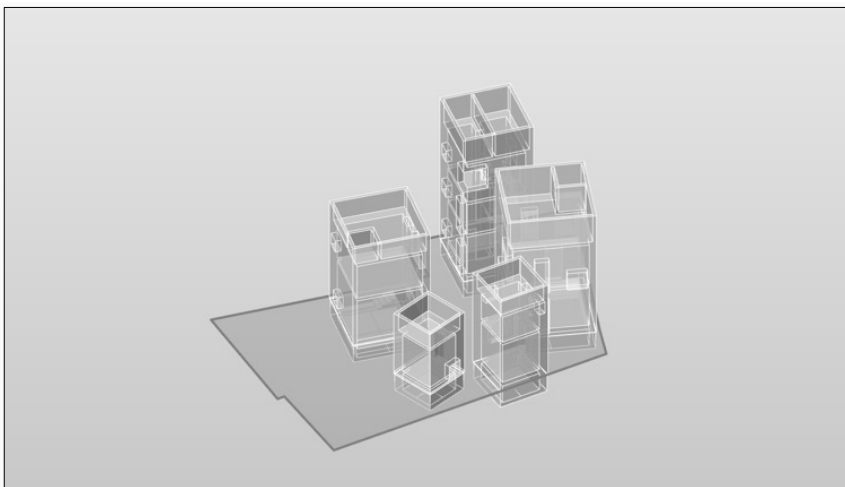


Figure 4.12. *boxComplete(s)*.

- Brep (*boxBBox*): the bounding box of the *box* (Figure 4.13).

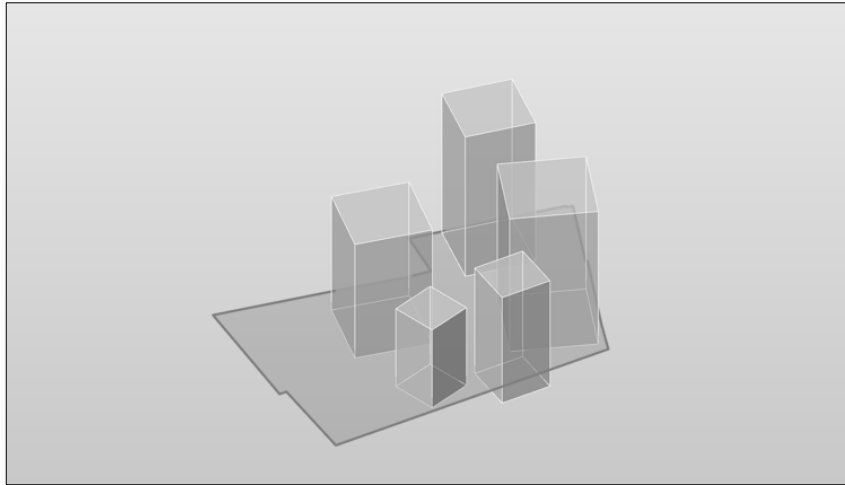


Figure 4.13. *boxBBBox(s)*.

- Brep (*boxTrees*): a simplified geometric representation of the rooftop trees (Figure 4.14).

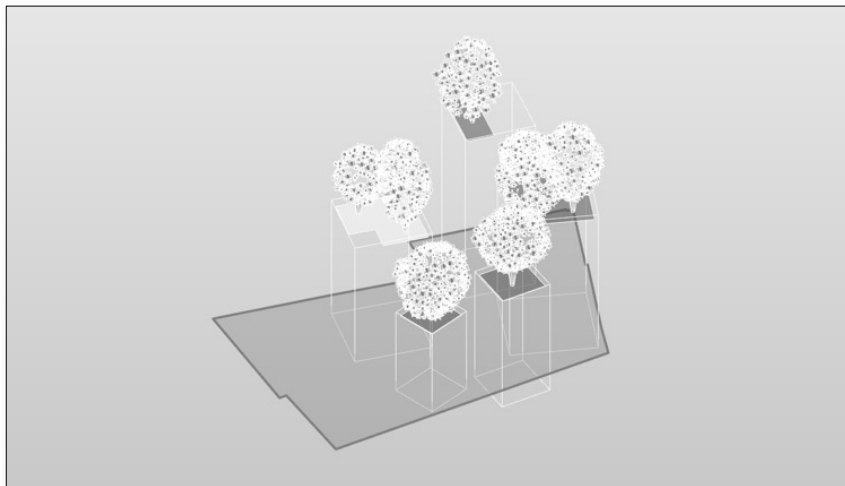


Figure 4.14. *boxTrees*.

- Brep (*boxLowDetail*): a simplified representation of each *box* without interior spaces, but includes description of fenestrations (Figure 4.15).

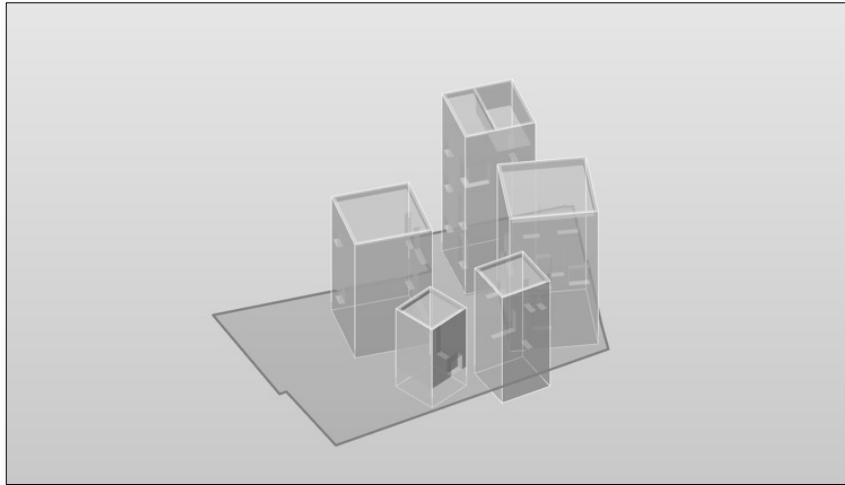


Figure 4.15. *boxLowDetail(s)*.

- Curve (*boxFenestrations*): 2D outlines of doors and windows (Figure 4.16).

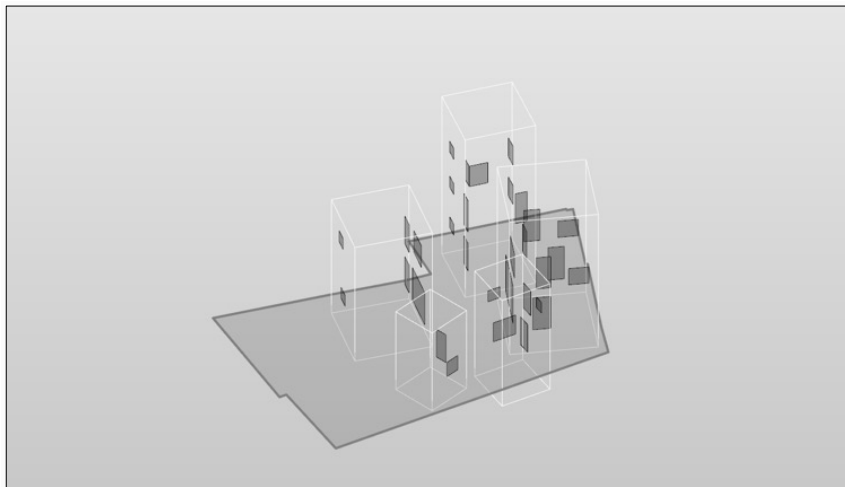


Figure 4.16. *boxFenestrations(s)*.

- Mesh (*boxSimpleTrees*): a simplified volumetric representation of the rooftop trees (Figure 4.17).

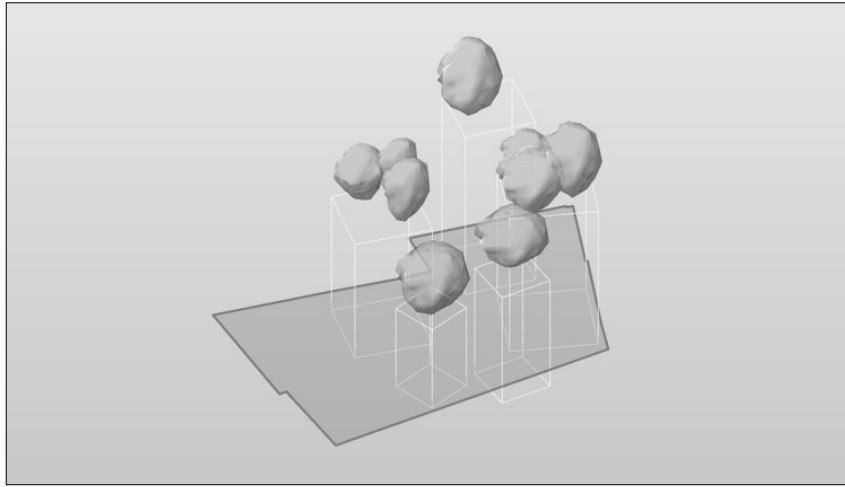


Figure 4.17. *boxSimpleTrees(s)*.

4.2.2. Controllers

In this research, formal disparity amongst design solutions may be evident in the overall parti of the HFT and on the interstitial spaces amongst the *boxes*. Because formal changes are not to be made to the five *boxes* in and of themselves, a decision was made to use five *controllers* to parametrically manipulate the *independent boxes*, including all encapsulated *independent objects*. A *controller* is a separate abstract model whose outputs may be used as input for the main model (Woodbury, 2010). Every *controller* is made of two associated elements, a parametric *boxPivot* and an *independent boxTrack*.

4.2.3. Parametric *boxPivot*

Transformations applied to a concrete *box* are directly affected by the *box's* associated *boxPivot*. Every transformation requires an *origin* to—for example—rotate or scale about. The origin may be *global* or *local*. Global origin is at the 3D center of the modeling environment, i.e., where values for X, Y, and Z equal zero. Alternatively, every object has a local *origin* associated with the object which may be called object *center* or object *pivot*. The conventional but not necessarily required location of object *origin* is at its geometric center, i.e., at the *center* of the 2D-outline of a 2D object or at the *center* of the 3D-volume of a 3D object. The pivot may also be considered the parent

transformation of its associated *object*, i.e., if the pivot is translated, the *object* is accordingly translated. Going forward I shall use the word *pivot*, as opposed to *center*, as the word “pivot” does not imply a specific spatial location for an object’s *origin*. To summarize, a *pivot* is the *origin* of a given object and it is necessary for all transformations.

For each *box* in the HFT, the associated *pivot* is also the *origin* of the *box*, i.e., the point in space from which a given *box* may be translated, and around which the *box* may be rotated. This *pivot* will be referred to as the *boxPivot*. *BoxPivot(s)* use the 2D outline of their associated *box* projected on the ground plane. For *box 01,02,03* and *05*, the associated *boxPivot* is located at the midpoint along the edge that is tangent to the property outline (Figure 4.18). For *box04*, the *boxPivot* is at the center of *box04*’s projected 2D outline on the ground plane.

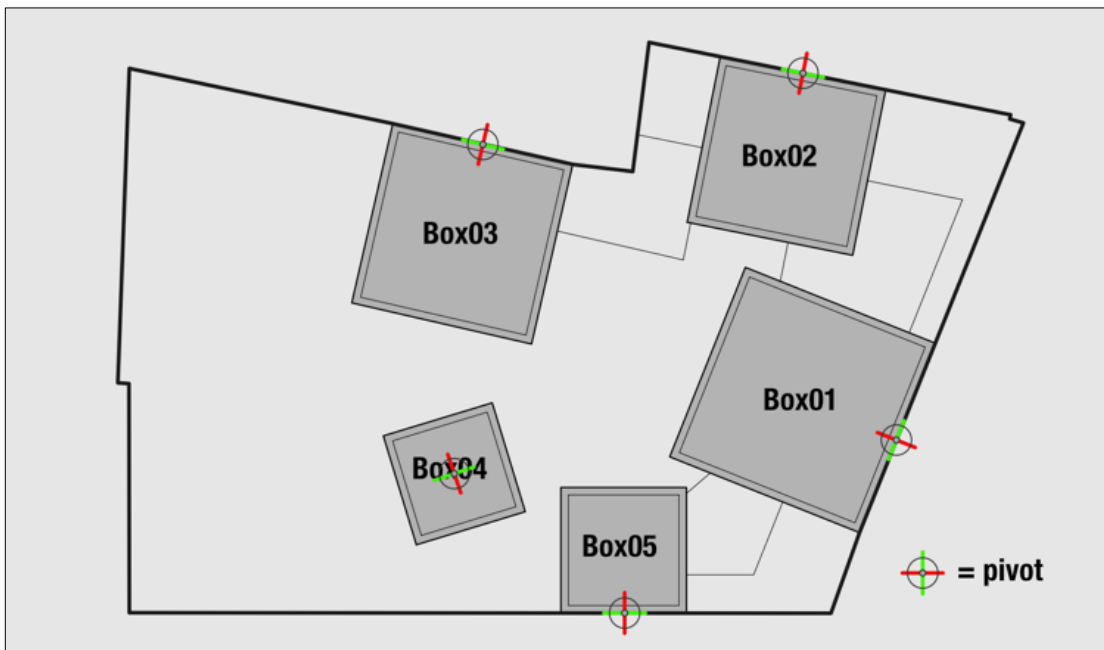


Figure 4.18. Tangency of *boxPivot(s)* associated with *boxes 01,02,03, and 05*. Centralized *boxPivot* associated with *box04*.

4.2.4. Independent *boxTrack*

To have a predictable control over its location in space, each *boxPivot* is constrained to an associated *boxTrack*. Each *boxPivot* and the associated encapsulated *independent objects* may slide (translate) along a curve which acts as a track (*boxTrack*). A decision was made to have five discrete positions per *boxTrack* to which a *boxPivot* may be translated.

In the original design for the HFT, four out of the five *boxes*—*box01*, *box02*, *box03*, and *box05*—have one edge tangent to the property outline (Figure 4.19). This tangency is considered as a guideline for creating each *boxTrack*. In general, each *boxTrack* remains tangent to the property outline unless there is an opportunity for deviation. For example, *box04* is the only free-standing *box* in the HFT that neither touches the property walls nor does it connect to the other *boxes* via the bridges on the 2nd floor. Therefore, *box04* slides along a track that may be described as *free*, i.e., a track that does not conform to the property outline. The *boxTrack* for *box03* is one that partially conforms and partially deviates from the property outline. Except for *box03* and *box04*, the remaining *boxes* have *boxTrack(s)* that are constrained to be uniformly tangent to the property outlines. Figure 4.20 demonstrates tangency, partial tangency, and free *boxTrack(s)* associated with the *boxes*.

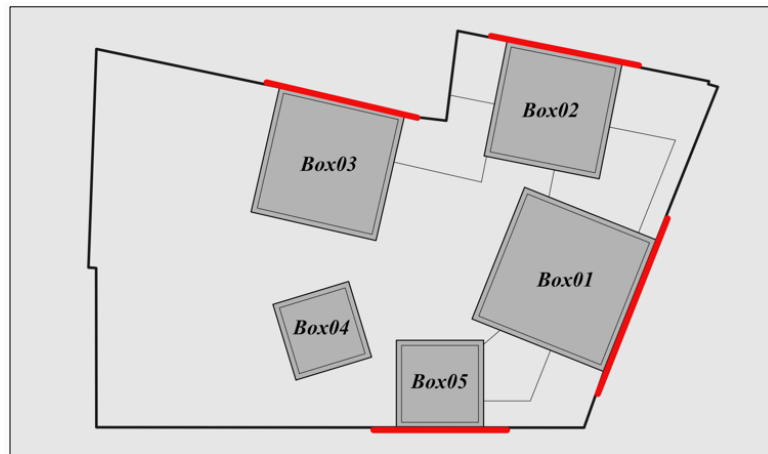


Figure 4.19. Tangency of *boxes 01, 02, 03, and 05* to the property outline.

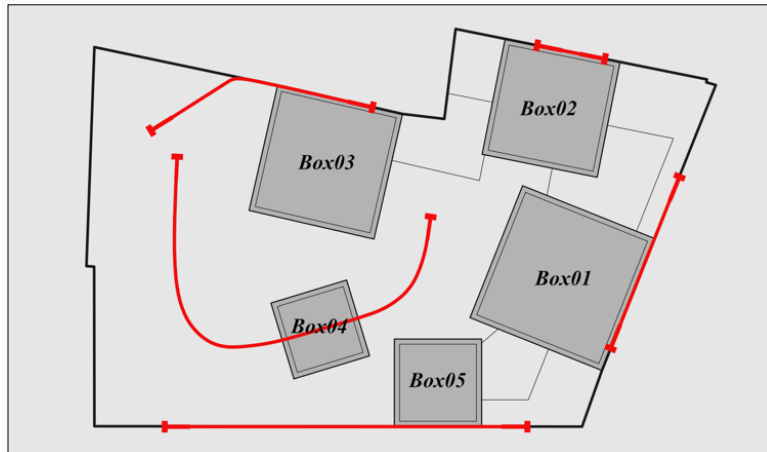


Figure 4.20. Uniform tangency of *boxTrack(s)* associated with *boxes 01,02, and 05*. Partial tangency of *boxTrack* associated with *box03*. Free *boxTrack* associated with *box04*.

Together, the *boxPivot(s)* and the associated *boxTrack(s)*, act as a *controller* for the associated *box(es)*. As a given *boxPivot* slides along its *boxTrack*, the associated *box* will update its location. Similarly, as the *boxPivot* rotates, the associated *box* and all objects within will rotate. Figure 4.21 demonstrates sample results of sliding and/or rotating the *boxPivot* for *box04* along its associated *boxTrack*.

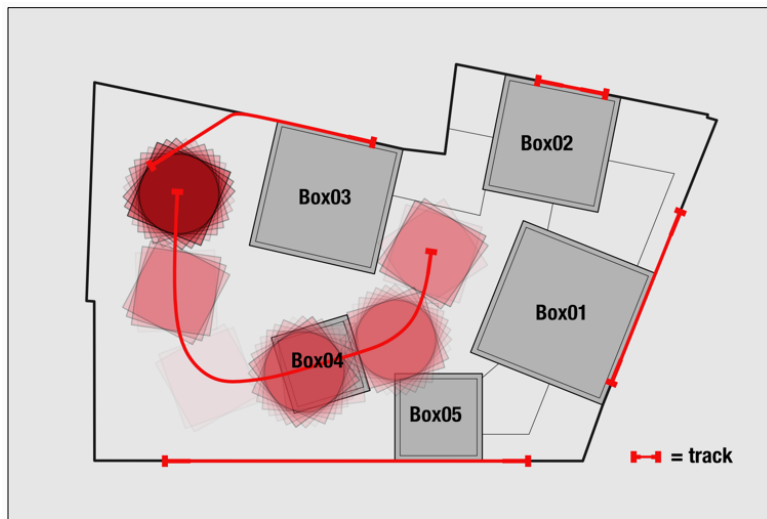


Figure 4.21. Sample possible *locations* and *rotations* of *box04* generated by using the parametric framework.

4.2.5. Identifying constraints

As the position and rotation parameters are varied, different design solutions may be generated. These design solutions may not necessarily be valid. Four constraints are introduced to the parametric framework to test for design solution validity. Design solutions that do not adhere to all of the following constraints are considered invalid. The following is a description of the four constraints accompanied with simplified algorithms.

The first constraint (*constraint01*) dictates that the distance between each *box* and all other *boxes* may not be less than a certain threshold. This constraint guarantees that there is always enough clearance between the *boxes* for circulation purposes. The algorithm for this constraint may be described as follows:

```
Set the solution to be valid
For each box:
    Check distance between the selected box and all other boxes
    If all distances are larger than the threshold
        Continue to check the next box
    Otherwise
        Set the solution to be invalid and stop loop
```

The second constraint (*constraint02*) dictates that no *box* should intersect any other *box*. In *constraint01*, the algorithm checks the distance between *boxes* using their projected 2D outlines. Thus, if a *box* is positioned entirely inside another *box*, the constraint may fail at detecting the invalidity of the design solution. *Constraint02* handles this problem by checking if any corner point of the projected outline of a given *box* is within the projected outline of another *box*. The algorithm for this constraint may be described as follows:

Set the solution to be valid

For each box:

 extract corner points from *box* outline

 If all points are **not** within any other *box* outline

 Continue to check the next box

 Otherwise

 Set the solution to be invalid and stop the loop

The third constraint (*constraint03*) dictates that the distance between HFT fenestrations, i.e., windows and doors, and the property outline may not be less than a certain distance. This constraint guarantees a certain clearance is maintained between the *boxes* and the property outline. The constraint measures the distance between the window, for example, and the property outline. This distance is measured from the center of each window and in the direction of the window's exterior normal. The algorithm for this constraint may be described as follows:

Set the solution to be valid

For each fenestration in all *boxes*:

 Check the distance between fenestration and property outline.

 If the distance is larger than the threshold

 Continue to check the next fenestration

 Otherwise

 Set the solution to be invalid and stop the loop

The fourth constraint (*constraint04*) dictates that *box01* may not be within less than a certain distance of a neighbors' window. This constraint guarantees a certain clearance for a specific neighbor's window to grant access to daylight. The algorithm for this constraint may be described as follows:

Check distance between neighbor's window and *box01*

If distance is larger than the threshold

The design solution is valid

Otherwise

The design solution is invalid

4.2.6. Improving design solutions validity check

To check for all the above constraints, for each design iteration, using detailed geometry significantly affects the computational efficiency of the parametric model. It increases the processing, i.e., the amount of time to translate and rotate each box, and increases the validity checking time for each design solution. Thus, an improved method is introduced to reduce the validity checking time. The enhanced method relies on an algorithm that makes use of some of the geometric representations, explained above, to simplify the validity checking process. To check for the *constraint01* and *constraint02*, the *boxOutlineCrv(s)* of each *box* is used (Figure 4.11). To check for *constraint03*, the algorithm uses *boxOutlineCrv* and a curve that represents the property outline. To check for *constraint04*, the algorithm uses an extruded *boxOutlineCrv* of *box01* and a 2D outline of the neighbor's window (Figure 4.22).

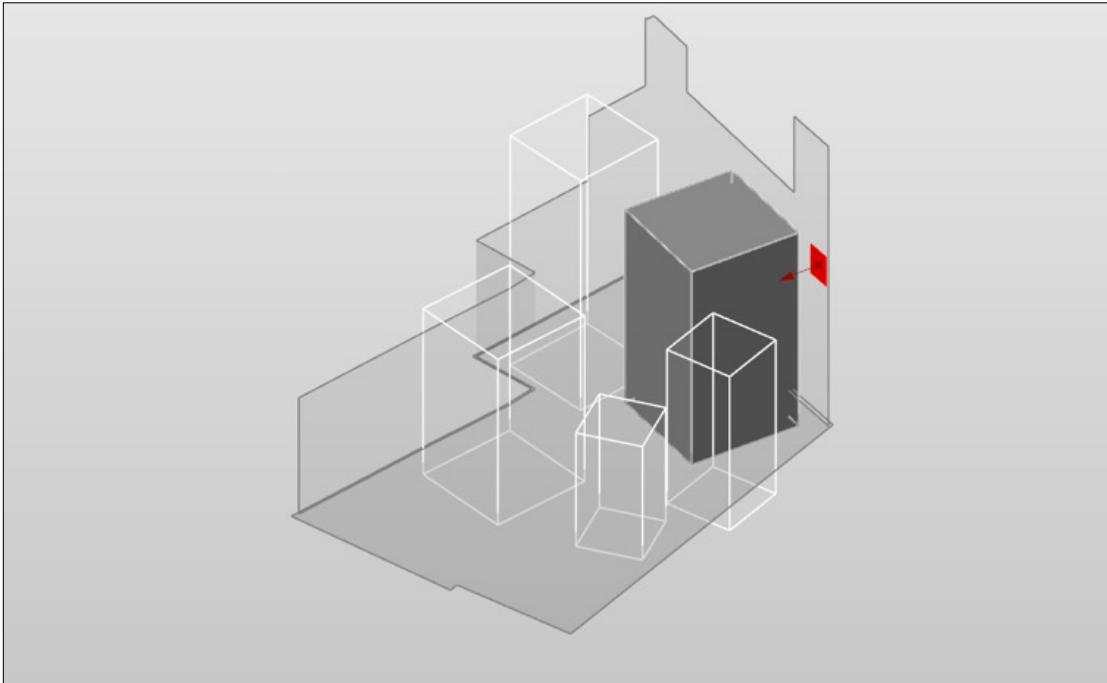


Figure 4.22. Extruded *boxOutlineCrv* for *box01* (dark gray) and a 2D outline of the neighbor's window (red).

By using the above parametric framework, we may arrive at formally diverse design solutions. Note that formal disparity amongst design solutions may be evident in the overall parti of the HFT and on the interstitial spaces amongst the *boxes*. That is, each *box* remains formally intact regardless of the *box*'s location and/or rotation. Also, note that the parametric framework is not inspired by the original architects' design process. Rather, the location and rotation parameters are chosen as examples to demonstrate possible scenarios of valid, formally disparate, design solutions that may be used for parametric design review. Figure 4.23 illustrates samples of different scenarios for sliding and rotating the five *boxes* of the HFT by using the created parametric framework.

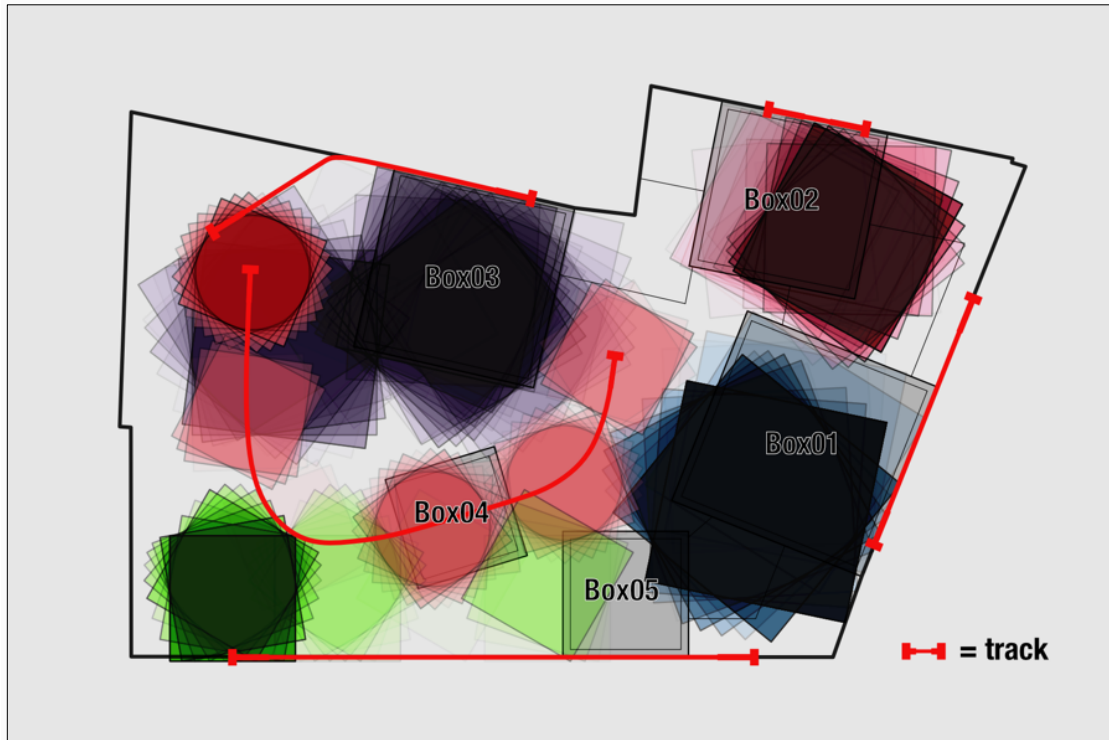


Figure 4.23. Different scenarios for sliding and rotating the five *boxes* of the HFT by using the parametric framework.

4.2.7. Parametric bridges

As previously mentioned, the HFT may be described as a set of five concrete *boxes*, four of which are connected via three steel bridges. The bridges manage the circulation on the 2nd floor, as well as provide much-needed shading and protection from solar radiation and rain on the 1st floor. Every time a valid design solution is generated per the above constraints, the bridges would accordingly be regenerated. The generated bridges are used as shading devices in solar radiation and daylight simulations, and as opaque objects that limit visual access to the interior spaces of the HFT in privacy simulations. The parametric model generates simplified bridges excluding any structural details and handrails (Figure 4.24).

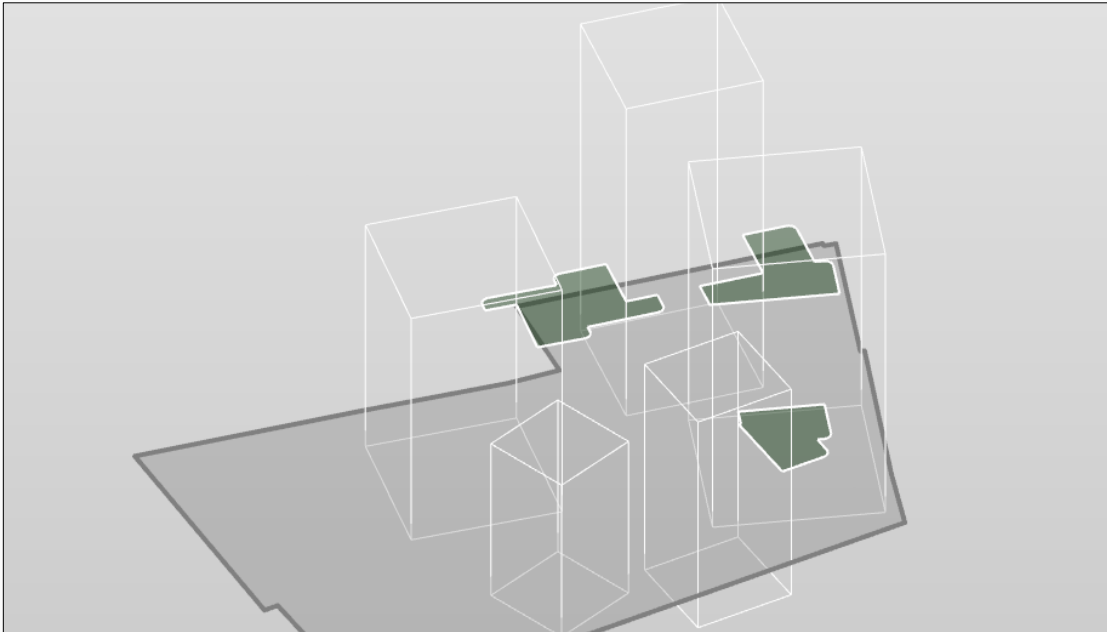


Figure 4.24. Simple bridges for circulation on the 2nd floor.

Several methods were tested to parametrically generate the bridges. The most robust method makes use of a Shortest Walk algorithm which is based on a topology calculator and the A* (A star) search algorithm (Piacentino, 2016). The idea of the algorithm is as follow: given a network (series of nodes and curves), a start node, and a goal node, the algorithm generates the shortest path that travels along the network connecting the start and goal nodes. The path is first processed then used to generate a surface that represents the bridge (Figure 4.25).

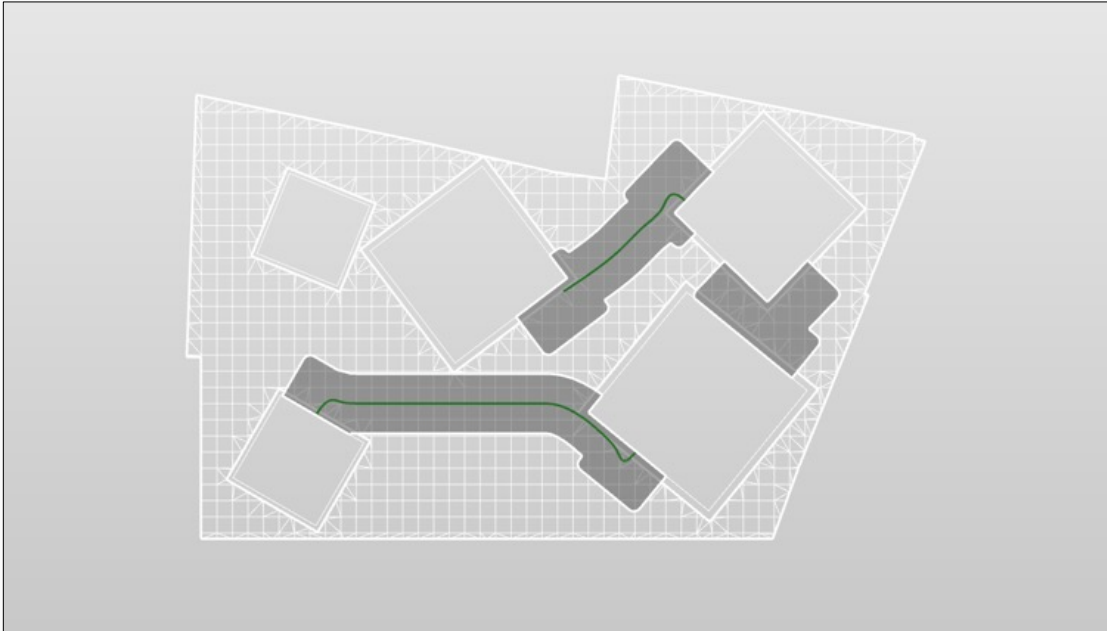


Figure 4.25. The use of Shortest Walk algorithm to generate bridges.

4.3. Multi-Objective Optimization (MOO)

Design is the intentional strive towards achieving certain project specific goals (Radford & Gero, 1988). When the intent is to engage multiple goals, a designer must exercise a process of design alternatives judgment based on trade-offs (Radford & Gero, 1988). A Manual process of trade-offs judgment may limit creativity and diminish the search space. As previously noted, generative design tools facilitated by evolutionary methods, such as Pareto Optimality MOO, may provide greater potentials for diverse, objective-based design solutions.

To arrive at a set of valid and optimized design solutions for the HFT, a MOO method is introduced to the parametric framework. The MOO method is facilitated by Octopus, an evolutionary multi-objective optimization plugin for Grasshopper. Octopus enables the search of design solutions through optimized trade-offs of multiple goals (Vierlinger, 2014).

Using the defined parametric framework, Octopus assigns position and rotation values for each of the five *boxes*. Generated design solutions are then tested against the

following set of constraints: *constraint01* guarantees enough circulation clearance is available between the boxes; *constraint02* tests if a *box* is spatially inside another *box*; *constraint03* tests for the availability of enough clearance between fenestrations, doors and windows, and the property line; *constraint04* guarantees a certain clearance for a specific neighbor's window to grant access to daylight. *Constraints 01-04* determine the validity of the solution. Once considered valid, the design solution is used to conduct the following three disparate simulations: (1) total solar radiation; (2) calculate the courtyard area; (3) privacy level. Each simulation outcome is used as a criterion with a specific goal in MOO. The algorithm for the MOO process may be described as follows:

<p>Generate random <i>transformation</i> values per <i>box</i></p> <p>Repeat the following until the predefined max number of generations is satisfied or user terminates process:</p> <ul style="list-style-type: none">Check for validity of design solution via <i>constraints</i><ul style="list-style-type: none">If valid<ul style="list-style-type: none">Apply <i>transformation</i> to <i>boxes</i>Run simulations and MOOOtherwise<ul style="list-style-type: none">Go back to: Generate new <i>transformation</i> values per <i>box</i>
--

4.4. Identifying Optimization Criteria

Competing performance criteria are defined to conduct MOO. Solar radiation, the size of the courtyard, and privacy measures of the HFT are considered as metrics to improve the collective performance of the model. The goal is set to find optimized design solutions where solar radiation is minimized, while courtyard size and privacy are maximized.

4.5. Simulations

Several simulations are conducted for the development of the test case. Some are done for architectural design optimization such as solar radiation, privacy, and courtyard size simulations. Other simulations are conducted to be used as a performance feedback to the user, during the design review, in the form of a dashboard.

Ladybug® and Honeybee® are used for all environmental analysis conducted in this research. Ladybug and Honeybee are packaged sustainable analysis plugins for GH. The plugins can make use of previously validated environmental analysis tools such as Radiance and Daysim for daylighting analysis, and EnergyPlus and OpenStudio for whole building energy analysis (Roudsari, 2014).

Time constraints and computational complexity are considered when identifying criteria for MOO. Simulating Solar radiation is computationally more expensive than calculating courtyard size or privacy vectors. While the former may take over a minute, the latter two provide feedback instantaneously, i.e., in real-time. Nevertheless, compared to other environmental analyses, solar radiation may be a less computationally expensive analysis, yet a representative one, thus was chosen for this test case.

Every simulation conducted for MOO may require a different set of inputs and specifications to measure a criterion. Thus, the following is a discussion of each criterion definition, goal, inputs, and results used in the MOO process.

4.5.1. Solar radiation

The annual total radiation is the cumulative solar radiations, both direct and diffuse, in kWh falling onto a single point (Roudsari, 2016). In this case, the simulation computes the results of a mass addition at each test point in kWh/m² multiplied by the area of the face that the test point represents (Roudsari, 2016). In general, solar radiation is undesirable in the summer and is desirable in the winter (Reinhart, 2014). However, due to the climatic conditions of the site, solar radiation is undesirable throughout the year. Solar radiation simulations may be conducted for daylight analysis or glare analysis. However, the goal for this simulation is to minimize the amount of solar

radiation falling on the building and courtyard surfaces, i.e., to minimize the heat gain throughout the year.

The model for solar radiation analysis is simplified in the way in which it does not consider doors and windows, nor does it consider the exterior fluting of the concrete. The model in (Figure 4.26) shows the five concrete *boxes*, steel bridges, and the courtyard as the surfaces onto which the amount of total Solar Radiation is to be computed. For this simulation, bridges handrails and details were omitted to accelerate simulation calculations, as well as to avoid any misrepresentation of elements that may occur due to Honeybee's tessellation algorithm.

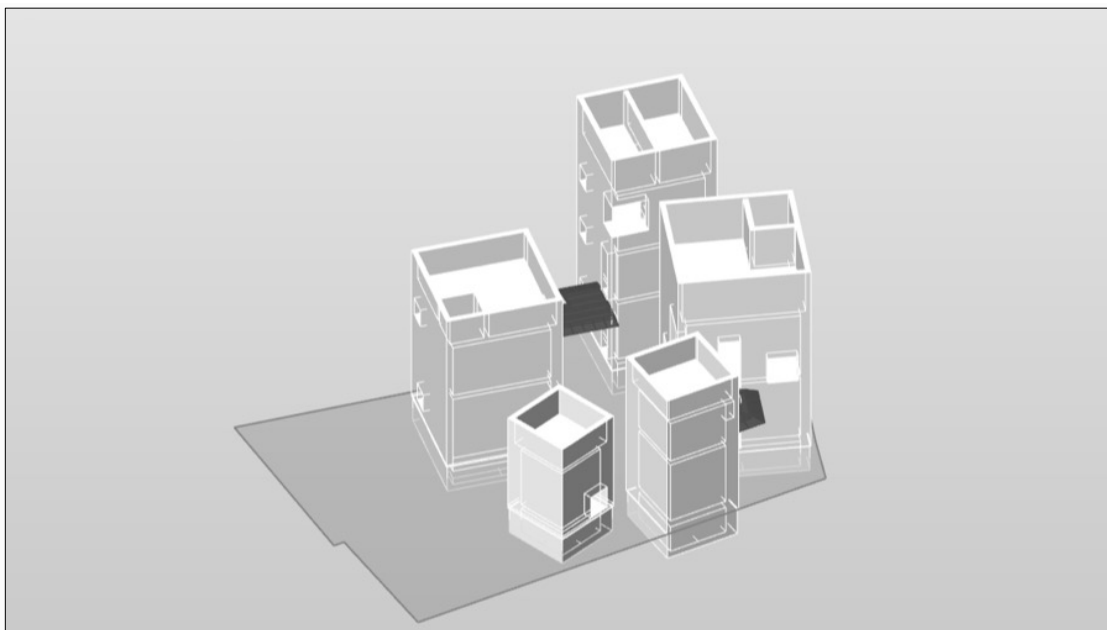


Figure 4.26. Solar radiation model.

The context model contains elements that may be considered as shading. Trees and existing buildings are amongst the elements that may be considered as context. The context model consists of two contextual elements. The first element is the massing of

the immediate neighboring buildings (Figure 4.27). This model only expresses the neighboring context as opaque solids.

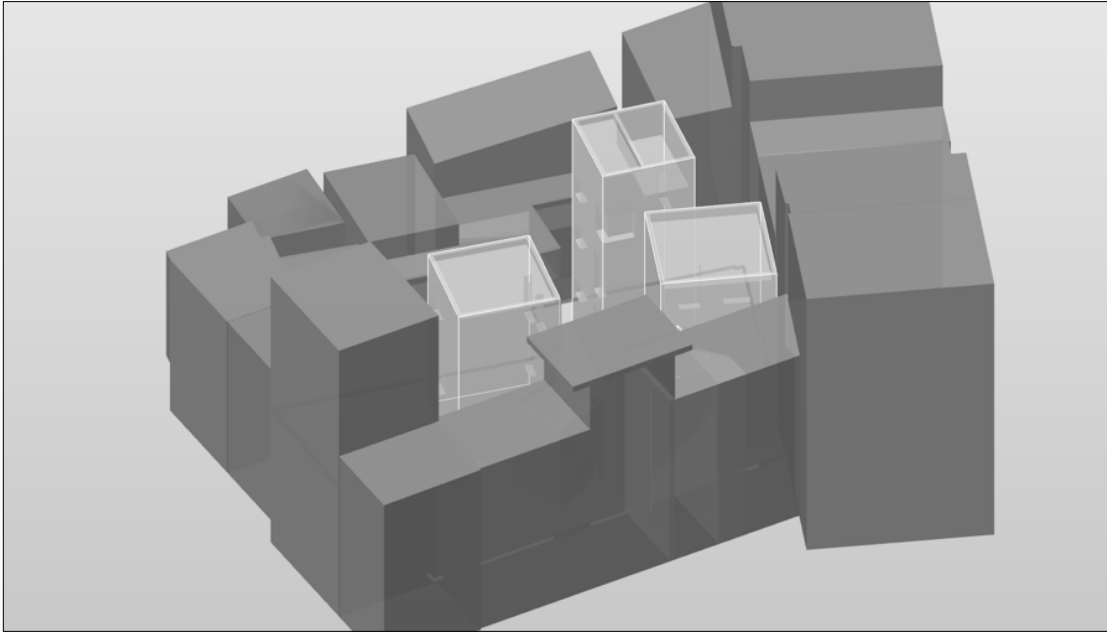


Figure 4.27. Massing context/site model.

The second element is the grouped combination of roof soil and trees. Figure 4.28 shows both contextual elements considered as shading. Literature suggests that tree canopies may be considered as perforated shading devices and therefore may permit solar radiation to pass through to surfaces beyond (Villalba, Pattini, & Correa, 2014). That is to say that trees are perforated obstructions that have a mix of zero transmittance and transmittance equal to 1 (Villalba et al., 2014). The amount of light that may pass through a tree is a function of its canopy density. For this research, the geometric model for tree canopies provides some level of perforation, but permeability percentage is not calculated (Bartie, Reitsma, Kingham, & Mills, 2011). The canopy foliage of each tree is generatively modeled as a series of intersecting planes to give the tree objects permeability (Figure 4.29).

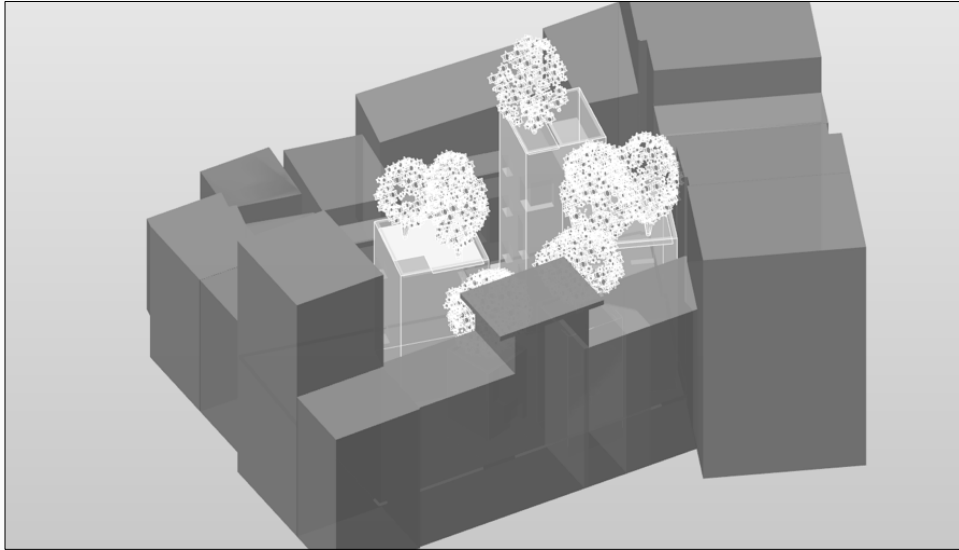


Figure 4.28. Massing context and abstracted tree models used as shading elements.



Figure 4.29. Sample of a perforated tree model.

For the calculation of the solar radiation, it is necessary to provide specific environmental information. Some of this information can be accessed from the EPW file

associated with the project location. For example, to simulate the annual amount of radiation falling on a surface, it is a prerequisite to have a calculated sum of the sky's radiation for each hour of the year. Other information can be unique to the analysis surface or mass in question. For example, it is necessary to provide a vector that represents the project north to conduct relevant and accurate simulations.

Solar radiation simulation requires two variable inputs. The algorithm for the radiation analysis calculates the amount of radiation that falls on particular sensor points in the analysis model. Therefore, the algorithm translates each solid or surface model object into a polygonal mesh model. The resolution, i.e., the density of subdivision in the mesh model, is controlled by a grid size integer variable. The grid size variable has an inverse relationship with the mesh density (resolution) and simulation time. A small grid subdivision yields more computationally-expensive analysis than a large one.

The results of this simulation may be numerical as well as visual representation feedback (Figure 4.30). The numerical output is the total amount of solar radiation falling onto the HFT. This value is the criterion used to conduct MOO where the goal is to minimize the total amount of solar radiation.

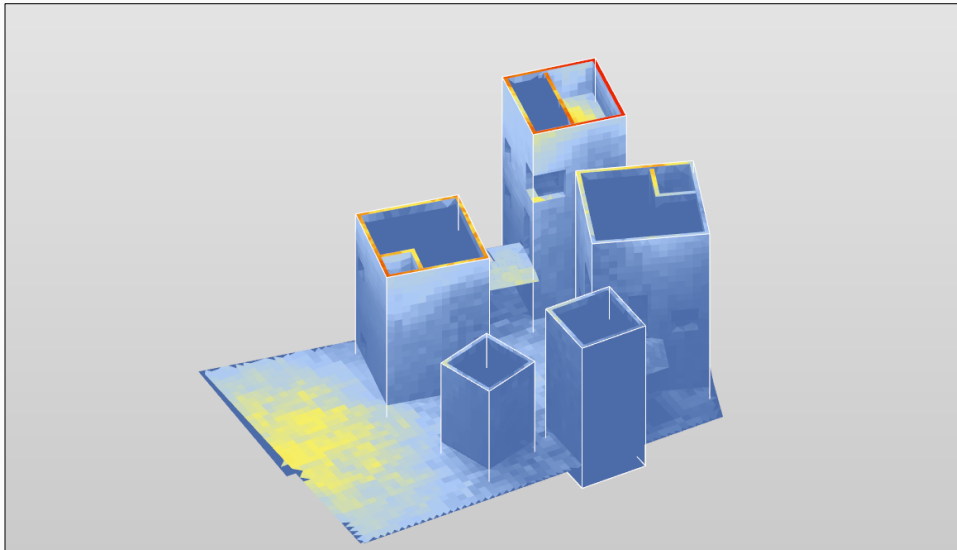


Figure 4.30. Solar radiation analysis visual feedback.

4.5.2. Courtyard size

The courtyard size simulation calculates the area of the courtyard for a given design solution. This simulation infers and approximates the size of the courtyard using the projected outline of the five *boxes* of the HFT on the ground plane. The algorithm creates a convex hull polygon which uses the projected center of each of the five *boxes* as a vertex and a corner point on the property outline (Figure 4.31). A polygon with all interior angles less than 180 degrees may be defined as a convex polygon. The outline of each *box* is subtracted from the original convex polygon to arrive at a more accurate estimation of the area of the courtyard. Thus, this simulation only reports the external area between the five *boxes* (Figure 4.32).

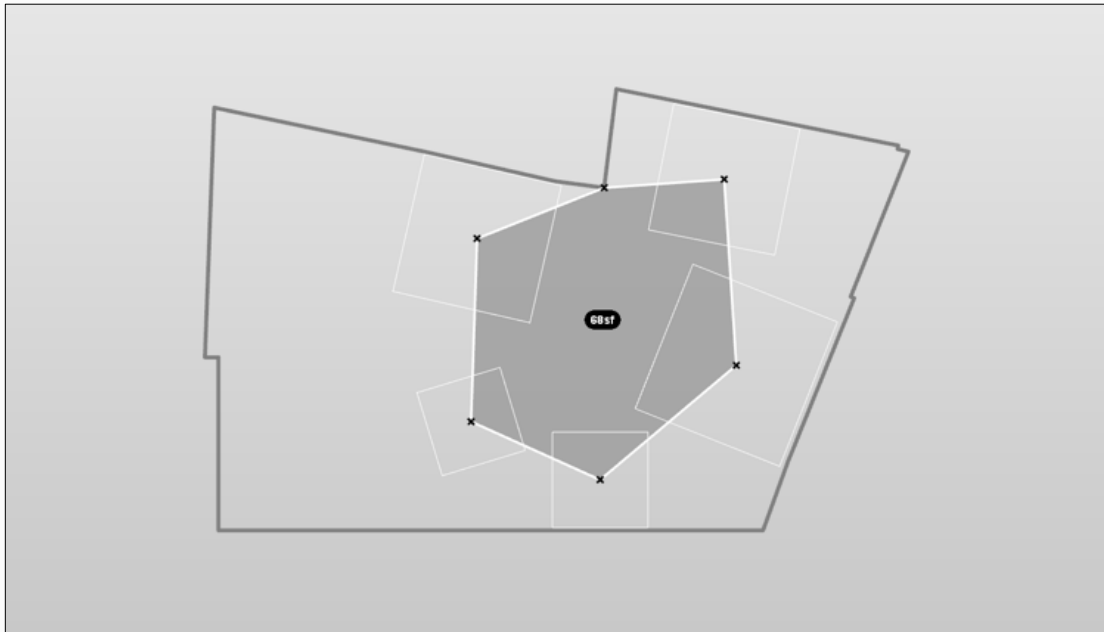


Figure 4.31. Convex hull generated from the center of each *box*.

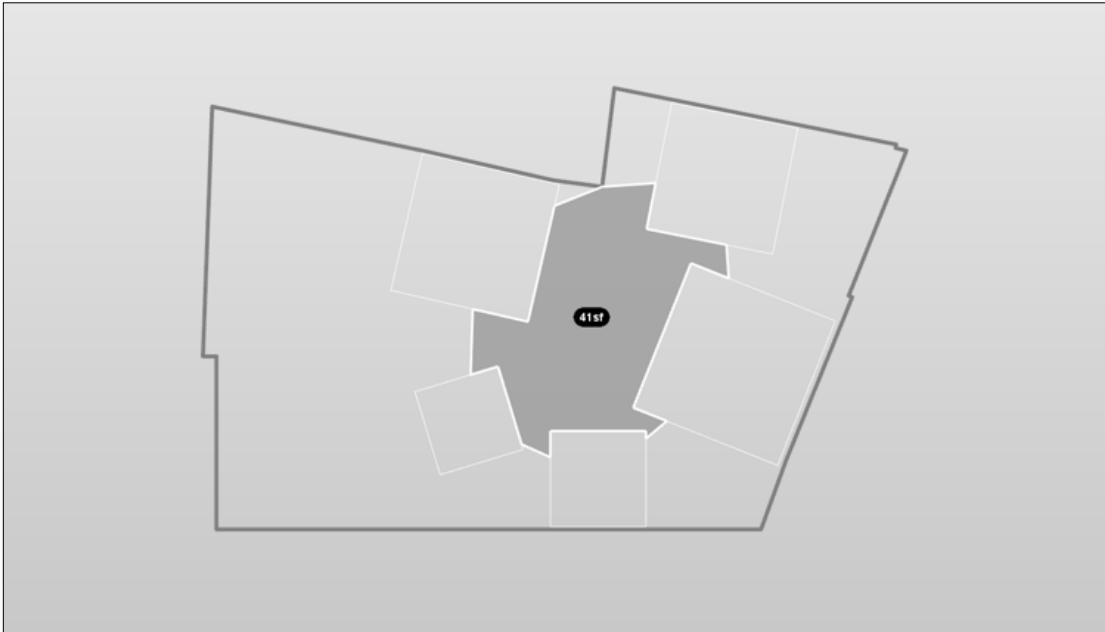


Figure 4.32. Reported area after subtracting the outline of the *boxes* from the convex hull polygon.

The analysis model for the calculation of the courtyard size only considers two-dimensional outlines for each volume. Thus, this is the simplest representation used in all simulations conducted in this study as it is purely two-dimensional.

The results of the courtyard area simulation are numerical. The numerical value represents the rounded calculated area of the courtyard in square meters. This area is a criterion to be maximized using MOO.

4.5.3. Privacy

The simulation conducted to measure privacy is not based on scientific evidence provided by the literature. The simulation calculates a rough metric of the privacy by mapping a vector starting at the center of each window from the neighbors to every window in the HFT (Figure 4.33). Obstructions, such as trees, bridges, and *boxes*, may terminate the vectors. The number of all remaining unobstructed vectors is reported, representing the number of instances when visual access—from the neighbors—to the interior spaces of the HFT may be possible.

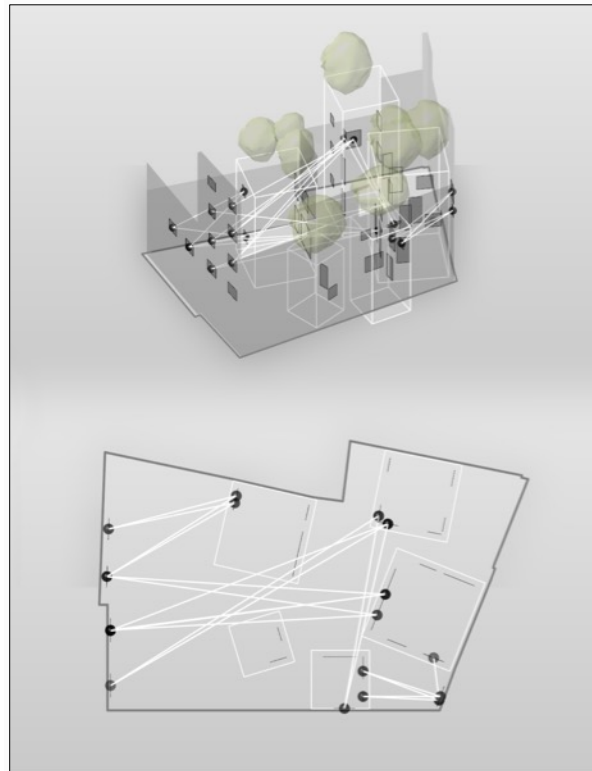


Figure 4.33. Top and isometric view of privacy vectors connecting neighbors' windows to HFT fenestrations.

The same model from the solar radiation analysis is used to conduct the privacy simulation. To calculate the privacy vectors, no distinction is made between analysis model and context model. All opaque objects that make the totality of the HFT—*boxes*, context, rooftop trees, and bridges—are considered as obstructions that can prevent neighbors from gaining visual access to the interior spaces of the HFT. All HFT fenestrations, doors and windows, use the same materials and construction type. Both use maximum area of transparency and aluminum as casing and framing (Figure 4.34). Thus, no distinctions are made between doors and windows for the privacy simulation. As previously mentioned, VTN Architects have strategically placed the windows either close to the ground or in the corners of spaces which would necessarily maximize the level of privacy for the HFT (Figure 4.35). Thus, the calculation of the privacy vectors always reports the worst-case scenario for visual access.



Figure 4.34. All fenestrations in the HFT use maximum area of transparency. Photograph provided by VTN Architects (H. K. T. Nguyen, personal communication, May 19, 2016).



Figure 4.35. Note the placement of window on the left where it is tangent to the floor and within close proximity to the corner of the room (H. K. T. Nguyen, personal communication, May 19, 2016).

Results for the privacy simulation are both numerical as well as visual. The numerical feedback provides an integer of the total number of instances where visual access may be granted to the interior spaces of the HFT. The visual feedback shows a series of vectors that anchored at the neighbors' windows and point towards the apertures of the HFT. The numerical feedback is used as a criterion in the MOO for which the goal is to be minimized.

4.6. Selection of Design Options

The MOO process was terminated After a total number of 123 generations. The Pareto front on generation 123 consisted of 54 valid design solutions (Figure 4.36). By considering the diversity of formal disparity amongst the design solutions, the author manually excluded solutions that may seem closely similar. The decision was made to only select ten design options out of 54 Pareto front solutions. The number of selected design options is rather arbitrary and may be interpreted as excessive.

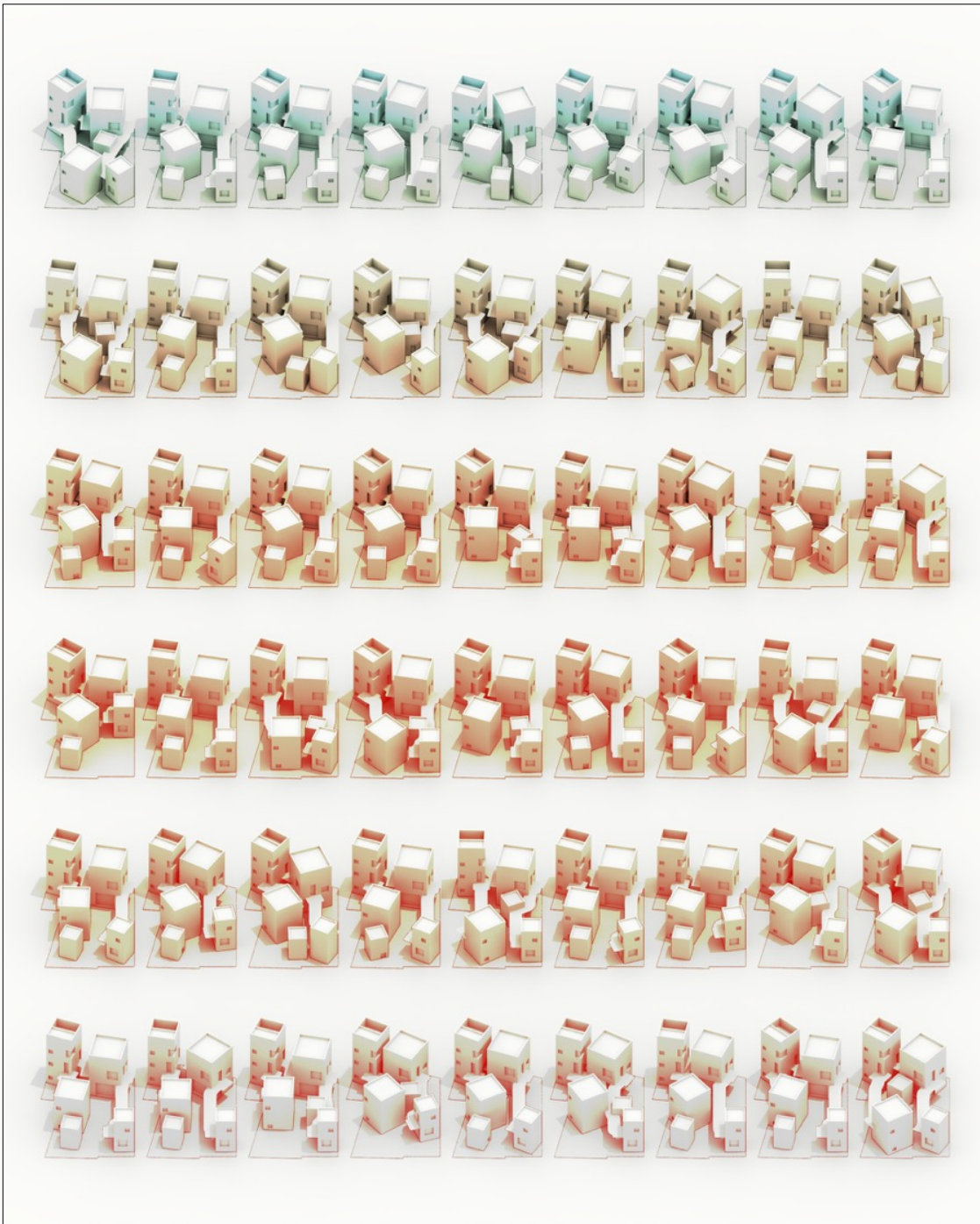


Figure 4.36. Pareto front design solutions generated using MOO.

The description of the design options selected by the author are as follows:

- *DesignOption01* is the original—non-optimized—design solution of the constructed HFT by VTN architects, i.e., not part of the MOO Pareto family.
- *DesignOption02* is one that is balanced.
- *DesignOption03* is one where *Solar radiation* is at a minimum.
- *DesignOption04* is where the *courtyard area* is at a maximum.
- *DesignOption05* is where the *privacy* is at a maximum.
- *DesignOption06* through *DesignOption10* are ones selected intuitively by the author from the Pareto optimal set based on the diversity of the design option formal qualities.

Nine out of the ten design options are selected from the MOO Pareto family.

Although one of the design options is not chosen from amongst the Pareto family, going forward, I shall refer to these ten design options as the *Pareto optimal design solutions* or a variation on the term.

4.7. Dashboard Simulations

The ten optimized design options selected above were subject to further performance-based analysis. Reinhart (2014), suggests the use of a dashboard for the quantitative evaluation of design solutions' daylighting performance. The dashboard reports different metrics that fit in different categories. This research uses the Reinhart suggested dashboard as a guide to conduct simulations that may be beneficial for the design review. These simulations fit in three performance categories for comprehensive daylight evaluation: daylight availability, energy efficiency, and occupant comfort (Reinhart & Wienold, 2011). The following simulations are conducted only for the ten selected Pareto optimal design solutions.

4.7.1. Daylight availability

Two annual metrics are reported in the daylight simulations, Spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI). Both metrics make use of the

same analysis and context models. All interior spaces are considered when simulating for both, the sDA and the UDI, metrics.

sDA is the percentage of analysis points across the analysis area that meet or exceed a certain illuminance level for a specific amount of occupied hours (Mohsenin & Hu, 2015). Per LEED 4.0, 55% of occupied space should meet $sDA_{(300,50\%)}$. That is, a building should have an annual daylight performance where 55% of the occupied space should have a minimum illuminance value of 300lux at least 50% of the typical occupation time. Therefore, an sDA result less than 55% means the building will not get the LEED 4.0 credit for this metric (“U.S. Green Building Council,” 2017).

UDI is the percentage of time during the occupancy hours that a test point receives a value between a minimum (100 lux) and maximum (2000 lux) thresholds (Nabil & Mardaljevic, 2005). The thresholds values are based on a survey of published work on occupants behavior in a daylit office environment (Nabil & Mardaljevic, 2005). If daylight illuminance is below the minimum threshold, it may not contribute positively to the visual perception of the environment. Alternatively, if daylight illuminance is above the maximum threshold, it may cause visual as well as thermal discomfort. The goal of this metric is to identify the area where the daylight illuminance values are between the minimum and maximum, i.e., the useful daylight illuminance (Nabil & Mardaljevic, 2005).

The analysis model for sDA and UDI simulations is made of two parts: a detailed surface model and a virtual sensor model. The detailed surface model represents all spatial and physical qualities of the design and environment. This model contains more information and variables than was necessary for previously conducted analysis for the MOO. The model considers the materiality of all surfaces including doors, windows, interior and exterior walls and floors, even rooftop trees, i.e., all the necessary information for glazing and opaque construction materials. The exterior fluted concrete surfaces are flattened to accelerate simulation speed. Therefore, each *independent box* is deconstructed into its constituent parts based on the different materials that make its totality (Figure 4.37).

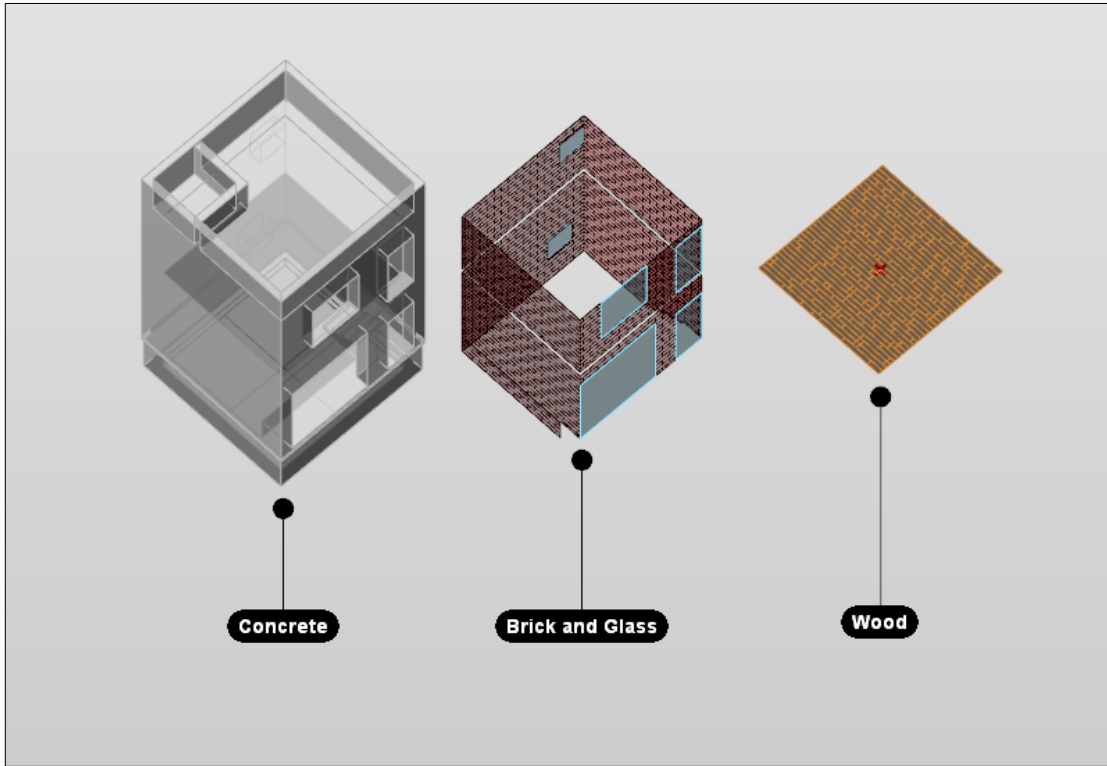


Figure 4.37. Example of deconstructing *box03* into its constituent parts.

Another model required for this simulation is a series of surfaces that represent a typical work plane. Typical work planes are set at no more than 30 inches above the surface of the floor (Reinhart, 2014). Each work plane surface is subdivided into a grid of upward-facing points (*testPoints*). These *testPoints* are virtual sensors, each of which reports the amount of daylight it receives based on the simulation. Through different automated calculations facilitated by HoneyBee, different metrics such as sDA and UDI may be reported. Figure 4.38 shows the grids necessary to conduct sDA and UDI simulations.

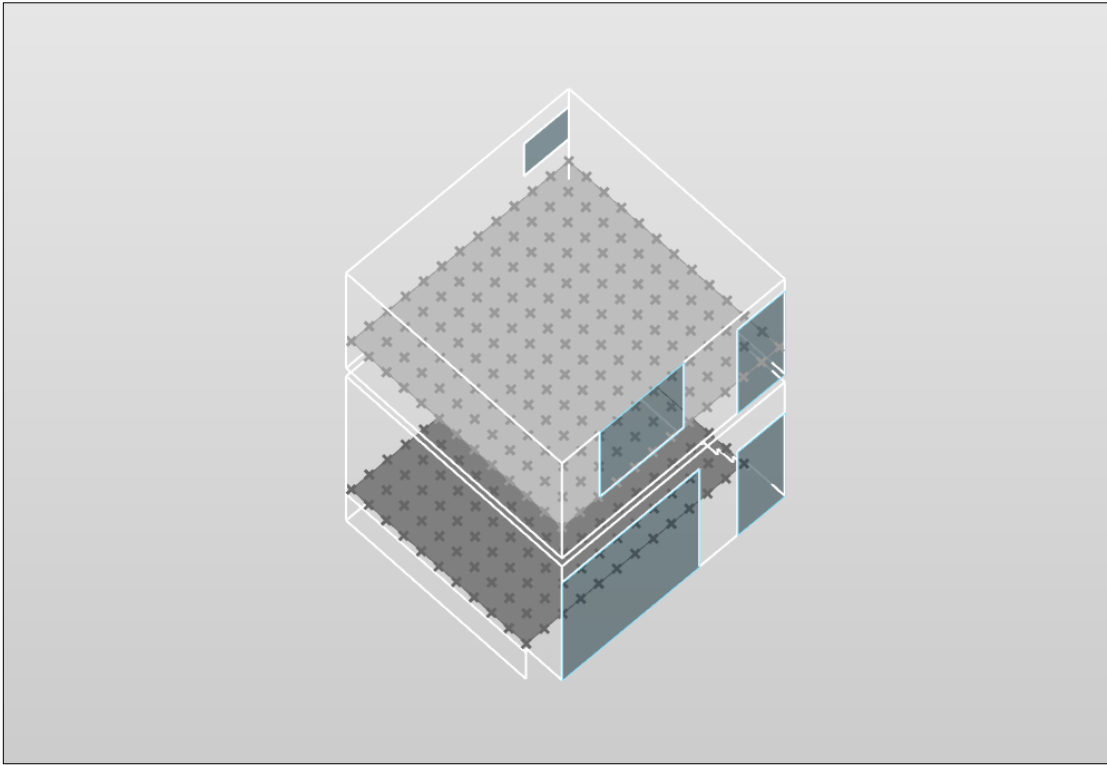


Figure 4.38. Sample grid necessary for conducting sDA and UDI simulations for *box03*.

Environmental variables for sDA and UDI are similar to ones from the *solar radiation* analysis: a valid EPW weather file and the correct north vector.

Simulation variables stem from multiple categories: grid spacing, occupancy hours, and materials. LEED 4.0 dictates that the grid must be square with points that are not more than 2 feet or 60 cm apart. The grid points are set to be 30 cm apart which resulted in 1196 total *testPoints*. The occupancy period is considered from 9 AM to 5 PM five days a week throughout the year. Six construction materials may represent all surfaces in the HFT: neutral, concrete, bricks, wood, ceramic, and glass. Equivalent custom Radiance Materials are created and assigned to different surfaces (“Defining Custom Radiance Materials,” n.d.). Reflectance, roughness, and specularity are specified for each material.

Simulation results

The result of an sDA calculation is a single numerical value. This numerical value is the percentage of simulation points that meet sDA criteria. UDI results are more complex to interpret numerically. UDI, in this case, is a list of 1196 values, each corresponds to a *testPoint*. Thus, to report UDI it is necessary to use spatial and visual representations (Figure 4.39).

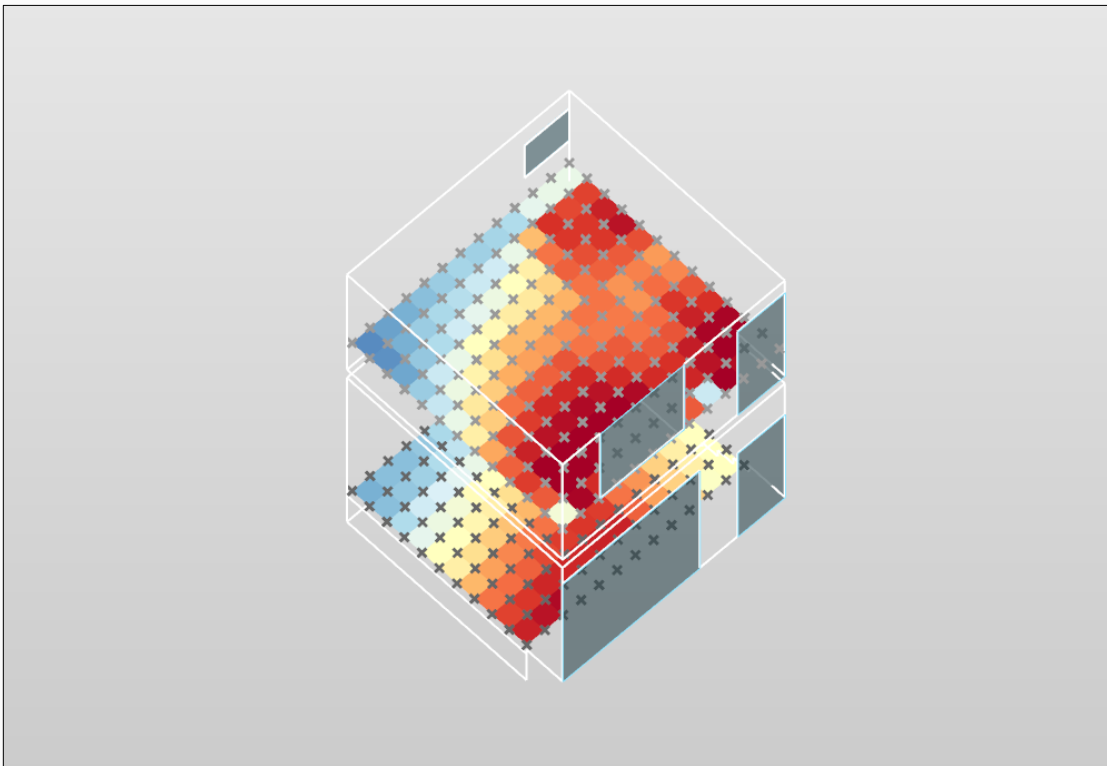


Figure 4.39. Sample of reported UDI results for *box03*.

4.7.2. Energy

Based on the performance dashboard suggested by Reinhart (2014), three metrics are reported for the energy simulations, a numerical Energy Use Intensity (EUI), a numerical Annual Utility Cost, and a graphical Monthly Utility Cost chart. All metrics are calculated using the energy simulation module in HoneyBee. The energy simulation

module in HoneyBee is built on top of EnergyPlus, which is a whole building energy simulation engine.

Energy Star recommends the use of EUI metric for all buildings (Energy Star, 2016). EUI is a benchmark expressing a building's energy consumption in relation to its size and other factors, such as cooling and heating loads. The annual utility cost, as well as the monthly utility cost, are also based on the different loads calculated by EnergyPlus.

The geometric model for this simulation regenerates for each of the ten optimized design options. EnergyPlus simulations are based on simplified representations of geometric models where all surfaces are planar (d'ENERGYPLUS, 2012). The parametric framework is setup to automate the generation of EnergyPlus-ready models for the ten optimized design options. For this simulation, the HFT model is divided into ten thermal zones. The automation of the process decomposes each *box* into its constituent zones. Each *box* is also deconstructed into its constituent elements: walls, ceilings, floors, roof, and glazing. These elements are then assigned an EnergyPlus construction type. Walls are assigned a multilayers construction type that consist of heavy weight concrete on the exterior, brick on the interior, and an air space that separate the two layers (VTN Architects, 2014). Floors and ceilings are considered as heavy weight concrete.

Similarly, the context model is also simplified into a series of objects with planar surfaces. The model includes outdoor ground, bridges, rooftop soil, and rooftop trees. The soil and trees are abstracted into cubes that represent the bounding box of each element. Figure 4.40 demonstrates the parametrically generated energy model zones and context surfaces for this simulation.

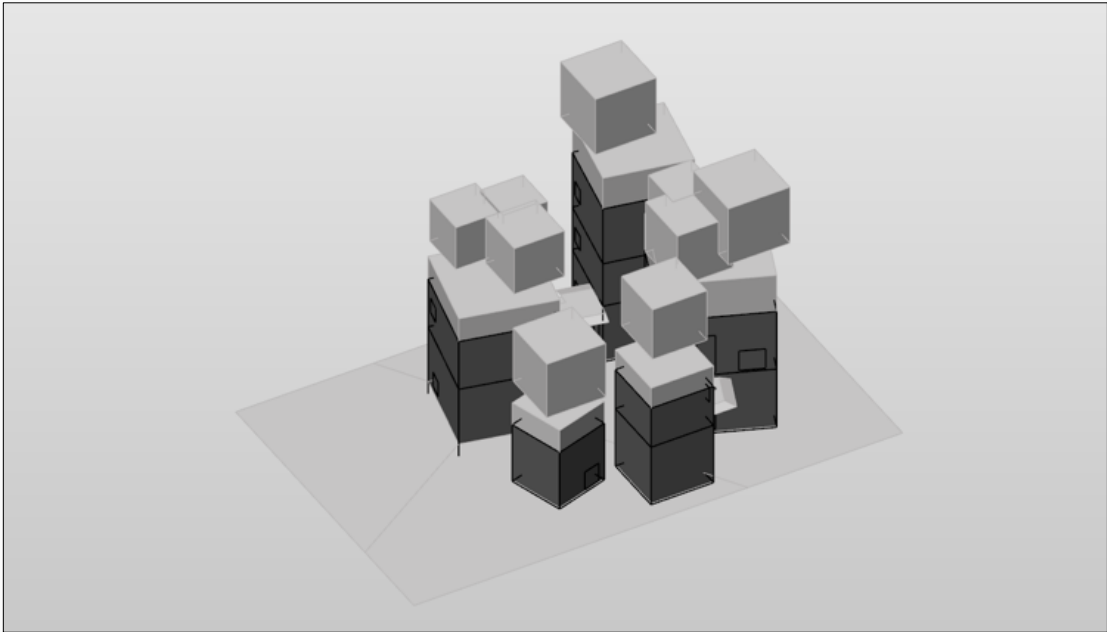


Figure 4.40. Energy model zones (dark gray) and context (light gray). Note that the floating cubes above each *box* are the roof top trees.

Similar to previously explained daylight availability analyses, this simulation requires a valid EPW file and a north vector, and analysis period.

There are few simulation variables to consider. For example, the analysis period must be specified. The simulation uses the same specified period for the daylight availability analysis. For example, each zone contains a parameter that categorizes it as a *conditioned* or *not conditioned* zone. There is no reference in the HFT documentations that explicitly define *boxes* as conditioned or not conditioned. However, inspection of the HFT photographs suggests that only the *box01*, *box02*, and *box03* have conditioned zones which are inferred from the allocated space for split unit AC systems on the roofs of the three *boxes*. Therefore, all zones in *box01* and *box03* are defined as conditioned, while all zones in *box04* and *box05* are defined as not conditioned. However, in *box02* only one zone out of three is categorized as conditioned.

Simulation results

The energy simulation provides the results for four different loads: cooling, electric light, electric equipment, and electric fan. Due to the hot and wet categorization of the climate zone, no heating loads are reported by the simulation. Figure 4.41 shows the result of this simulation for the DesignOption01, among the ten selected design options in the Pareto front.

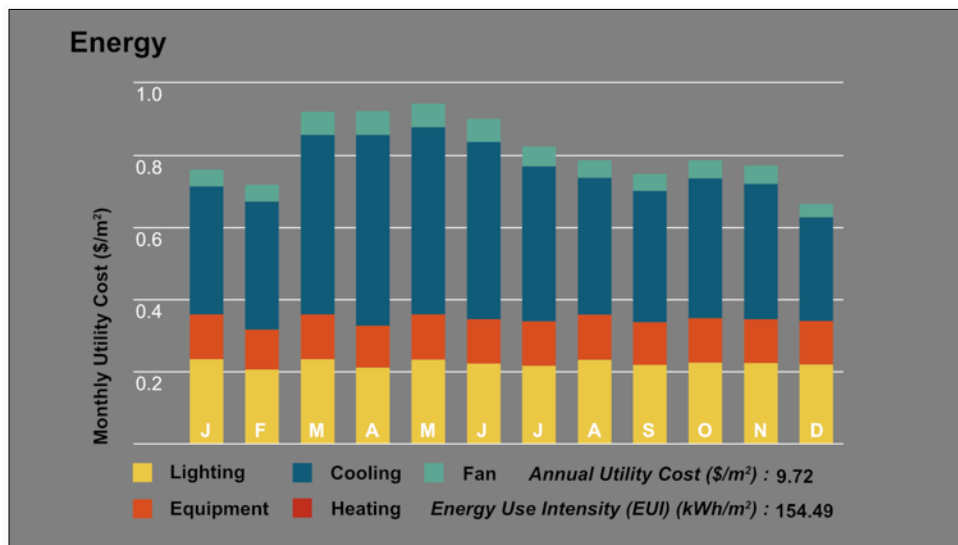


Figure 4.41. Sample of reported energy simulation results for *DesignOption01*.

4.7.3. Comfort

Glare probability temporal map is the only metric simulated for the comfort category for the dashboard. The simulation estimates the potential for glare in interior spaces by calculating the annual percentage of the floor area in direct sunlight (Mackey, 2015). To do so, the simulation requires a list of sun vectors and sun vectors' illuminance values. Sun vectors that hit the *testPoints* are accumulatively recorded.

The simulation model and context model are the same as ones already reported for the *daylight availability* metrics. However, in addition to EPW file, north vector, and occupancy hours, the environmental variables are more explicitly defined. The

simulation removes sun vectors below illuminance threshold to account only for illuminance amounts that may contribute to higher glare probability.

Simulation results

The results of this simulation are represented via a temporal map (Figure 4.42) and a spatial representation of the glare probability using the input testPoints (Figure 4.43).

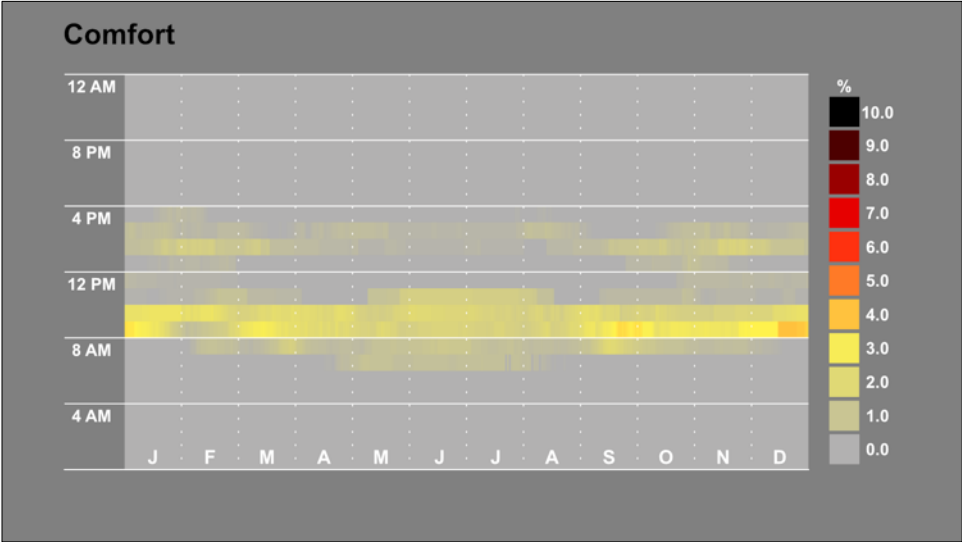


Figure 4.42. Annual glare probability temporal map for *DesignOption01*.

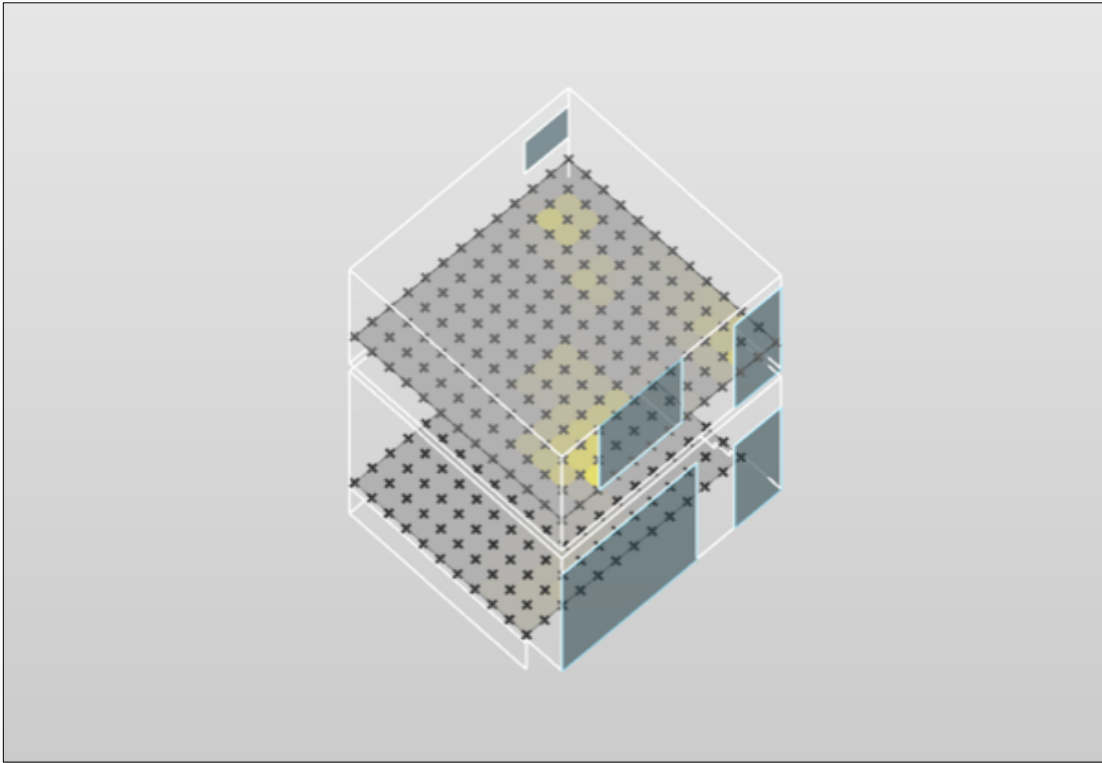


Figure 4.43. Sample of reported glare probability results for *box03*.

4.8. Summary

This chapter provides the details for the selection of the test case – an architectural project used to demonstrate the proposed PDR interface. The HFT project is selected as the test case project for this research. A parametric framework of the HFT is created to allow for alternate design solutions. The parametric framework relies on constraints that guarantee the generation of valid design solutions. By integrating a Pareto Optimality method in the filtering and selection of design options, we arrive at a set of optimized, objective-based design solutions. Ten design options are selected from amongst the Parato front family to be reviewed using the proposed method. The optimized design options are subjected to further simulations necessary for the creation of a *daylighting evaluation dashboard*.

5. PARAMETRIC DESIGN REVIEW USER INTERFACE PROTOTYPE

This chapter is made of three parts. The first part is the processing of geometric and non-geometric data for use in a game engine. The second part explains the outcome for the proposed Parametric Design Review (PDR) interface. Finally, some explanation of the framework for PDR interface is provided.

5.1. Processing of Geometric and Non-Geometric Data

To build a prototype that demonstrates the proposed method, geometric and non-geometric data were transferred from the modeling and simulation software to a game engine. In general, models exported from CAD and BIM software are not necessarily efficient for use in interactive VE. In fact, interoperability may be one of the most reported limitations against the integration of CAD/BIM and game engines (Bahar et al., 2013; Figueres-Munoz & Merschbrock, 2015; Lehtinen, 2002; Sallkachat & Choutgrajank, 2003; Shiratuddin & Thabet, 2011; Yan et al., 2011; Yoon et al., 2004). While it is possible to transfer geometric BIM/CAD data to game engines, the resulting models may not be efficient for texturing or real-time interaction. For example, FBX® models exported directly from Revit to a game engine lack material assignment because exported FBX files from Revit have encrypted textural properties (Altabtabai & Yan, 2015). Exported objects also lack some necessary hierarchy where for example a door and a door-frame are usually considered as one object. Additionally, higher mesh-resolution of the relatively large number of objects can prevent the direct use of BIM/CAD models in real-time VE.

Nevertheless, today some Digital Content Creation (DCC) software support a more robust workflow, even bi-directional interoperability, from and to game engines (Foundry, 2017). This seamless workflow not only solves interoperability limitations but also supports a “What You See Is What You Get” (WYSIWYG) approach. A WYSIWYG approach, facilitated by Physically Based Shading (PBS), guarantees that objects created and visualized in DCC software will look nearly the same when brought

into a game engine (Darknell, 2016c). PBS is a consistent and reliable rendering method to simulate materials' interaction with light in a way that closely resembles reality (Lopez, 2014). PBS process relies on image texture maps to modulate or mask different materials and their attributes on a surface (Körner, 2015).

The DCC software, MODO® 10.2v1, was utilized as a mediator to adjust and prepare CAD/BIM models for use in a game engine. MODO 10.2 was used in this research due to its significant capabilities in real-time VE content creation (Foundry, 2016). The software was used to create hierarchical relationships amongst modeled elements, alter and optimize geometric data, apply PBS textures, bake textures into image maps, and export game-ready models.

Two types of data are required for the development of the prototype: geometric and non-geometric data. The geometric data were processed into objects that are efficient for real-time interactive VE. Non-geometric data in the prototype are object parameters and simulation results. These data were brought into the game engine in their original format, are translated into bitmap images, or were converted into geometric data and texture maps via texture baking. The following discussion explains the background and workflow of creating game-ready models from their BIM/CAD counterparts.

5.1.1. Model hierarchy

DCC software and game engines have a variety of *item* types. These items may be *scenes*, *meshes*, *lights*, *cameras*, *locators*, and other types that are unique to a DCC software. The most relevant item types for the creation of this prototype are *scene* items, *mesh* items, and *locator* items. The naming convention of these items come from MODO, so while other software may have similar item types, the naming convention could be different.

A *scene* item is the file which contains all other items. A *mesh* item is a container for the polygonal data structure. A *locator* is an empty item that DCC software and game engines may have (Figure 5.1). Locators are autonomous items that can be transformed independently. Therefore, not only can *locators* be positioned and animated autonomously from other items, but they also can be used in a *hierarchy*. A hierarchy is

a term used in DCC software and game engines to refer to parent/child relationships, grouping, and ordering of items in a scene. A *parent* item gains control over children items and their transformation, i.e., if a parent item is transformed the child item inherits the transformation. However, *parent* items do not inherit children's transformations. Conventionally, an empty locator serves as a *base* or *root* parent item in a hierarchy (Darknell, 2016a).

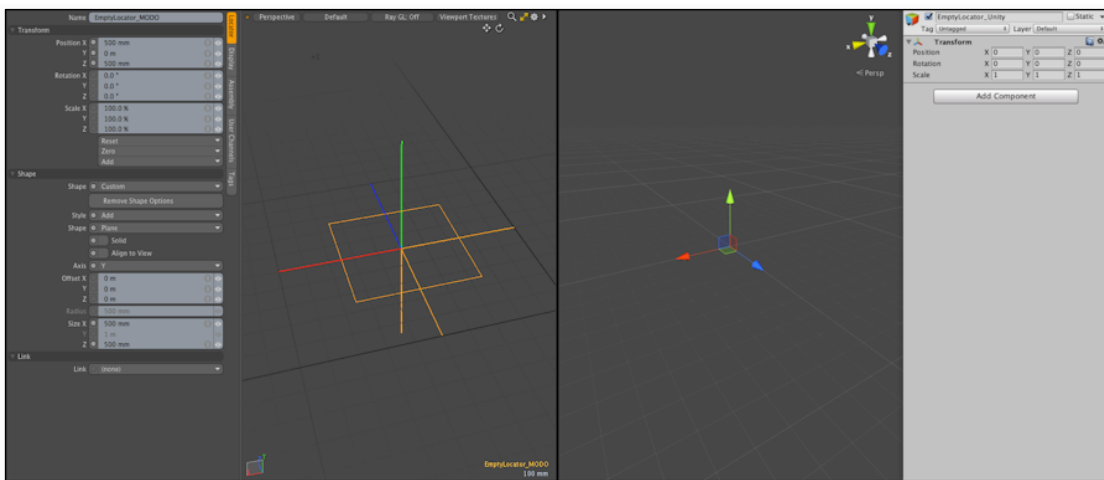


Figure 5.1. Empty locator in MODO (left) and Unity (right). Note the mutable transformation values in both cases.

In MODO, the model for the HFT was organized into a logical hierarchy that facilitates better object management down the line. Each *box* was made a child of an associated empty locator (*boxLocator*). For example, *boxLocator01* was made root item of *box01*. All objects within *box01*, e.g., walls, floors, windows, doors, furniture, and MEP were also made children of *boxLocator01*. Other *boxLocator(s)* for *boxes 02-05* followed the same hierarchy convention. Thus, each *box* and all objects within is an autonomous entity that can be manipulated independently from other boxes in a scene. Figure 5.2 demonstrates the hierarchy of *boxLocator01* in MODO, as an example.

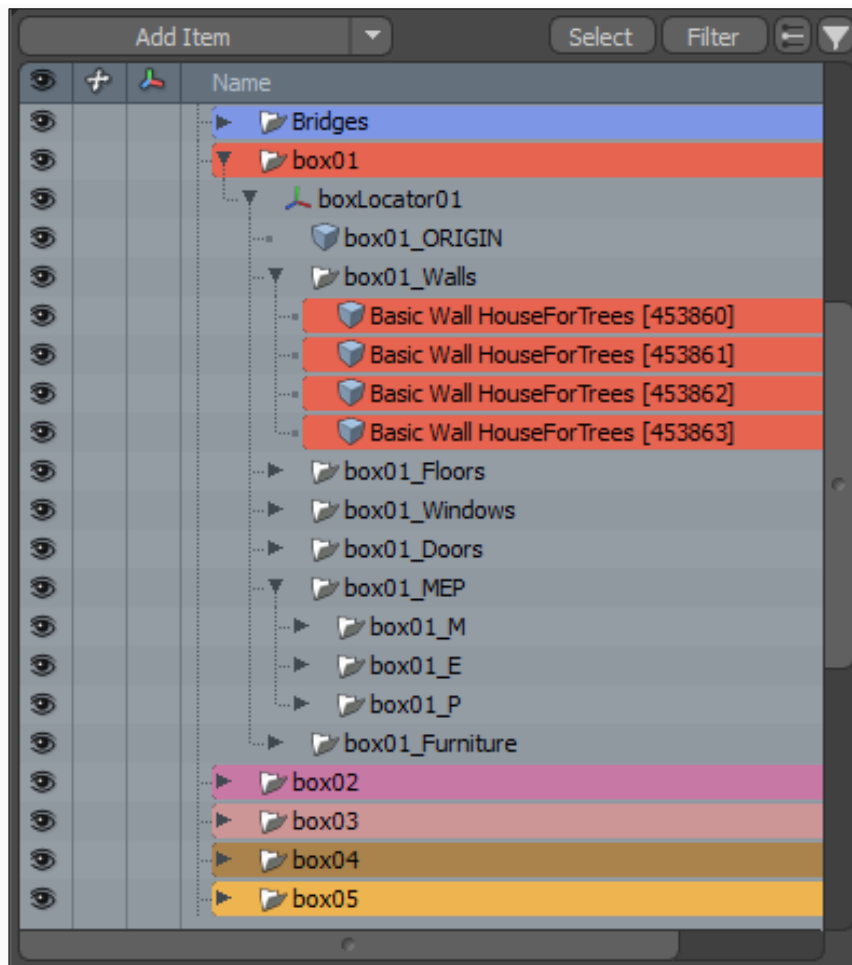


Figure 5.2. The *boxLocator01* hierarchy in MODAO.

The use of this logical hierarchy made it possible to use the same models for the five *boxes* to represent all ten optimized design options. For the ten optimized design options, the *world location* and *local rotation* of each *box* were recorded in Rhino. The *world location* is the *box's* projected geometric center on the ground plane. The *local rotation* is the amount of which the *box* is rotated around its *world location*. Together, the world location and local rotation provided the *transformation data* necessary to translate and rotate the *boxes* into any one of the ten optimized design options, i.e., animate the morphology of the *boxes* from one design option to another. For example, there are ten

possible transformations for *box05*. Each holds the *box*'s world location and local rotation for one of the design options.

The *boxes* and their contents may be translated and/or rotated. In MODO, a series of empty locators were used to record and export these *transformation data* from MODO to Unity. Figure 5.3 shows the ten transformation locators for *box04* where each locator holds the transformation data for *box04* in one of the ten optimized design options.

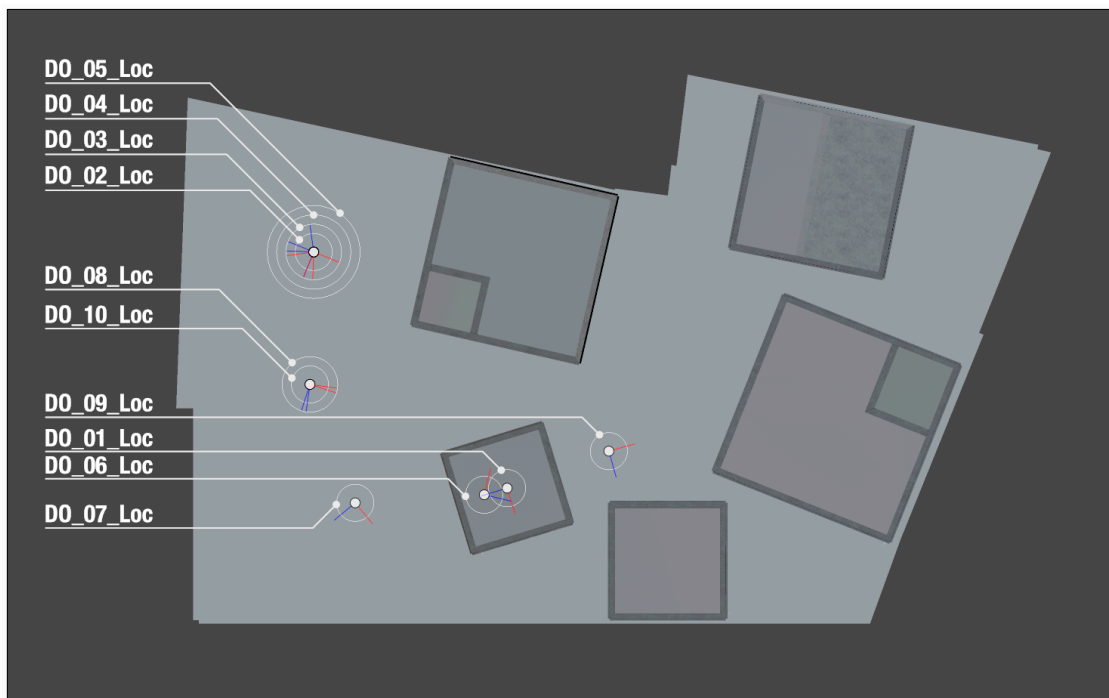


Figure 5.3. Ten transformation locators for *box04* optimized design options. Note the different sizes of some locators are graphical additions to indicate overlapping locations amongst design options.

While the *boxes* may be translated, the grounds and bridges for the design options do not have the possibility to be transformed. Nevertheless, the ground plane and bridges of the HFT must conform to the ten optimized design options. Therefore, there are ten different detailed models of the bridges and another set of ten models for the ground. Each one is associated with one design option.

The two main points are: (1) the use of the hierarchy made it possible to generate all design options by using a single instance of each *box*; (2) through the use of locators, the *world location* and *local rotation* were recorded for use in the game engine.

5.1.2. Mesh density

An important concept to grasp for game engine content creation is the notion of mesh resolution, i.e., *low-polygon count (low-poly)* versus *high polygon count (high-poly)* meshes (Figure 5.4). A low-poly mesh is one that is low in resolution, i.e., contains a comparatively small number of polygons. A high poly mesh, on the other hand, is usually made of very dense and higher count of polygons where all details are expressed using geometric data. Where interactivity is not required, e.g., high resolution still renderings, high-poly models may be utilized. However, for real-time applications, it is necessary, at the moment, to use low-poly meshes to maintain an imperceptible high frame rate per second (McDermott, 2010).

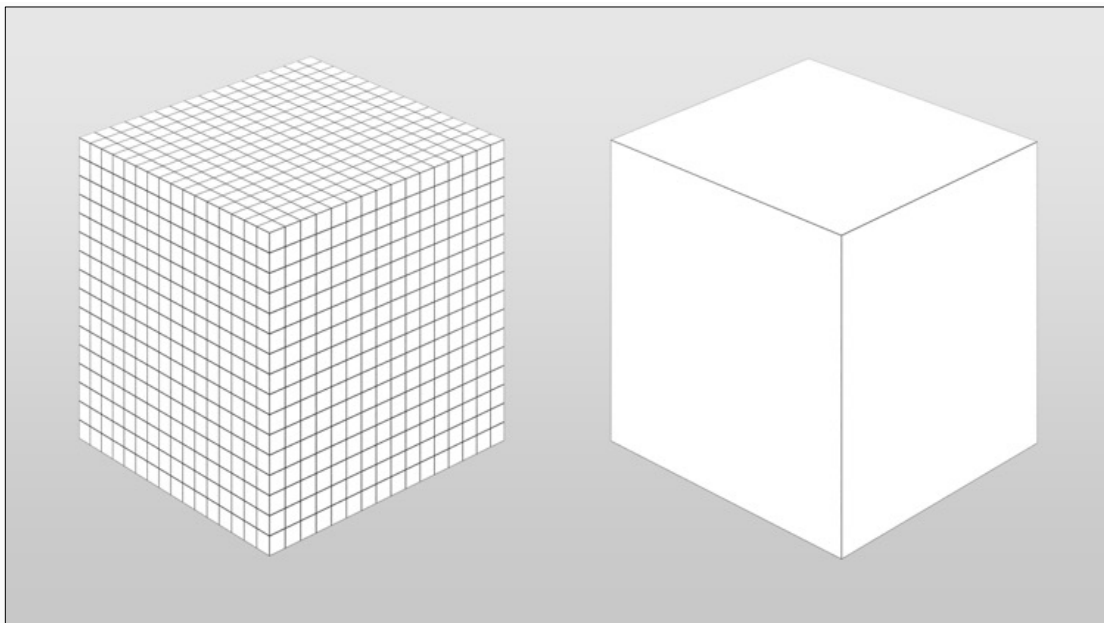


Figure 5.4. Low-poly mesh (right) and high-poly mesh (left).

Artists and game developers usually generate high fidelity assets and textures maps in the process of making a video-game or interactive environments. For example, they may use digital sculpting software that rely on very dense meshes and high-definition texture maps at the beginning of the ideation and asset creation process. However, having that fidelity requires high-poly meshes to simulate, for example, folding fabrics, surface scratches, and skin pores. The same can be said about geometry generated from CAD packages, where to stay true to the designers' intent and attention to detail, heavy meshes are created for rendering or rapid prototyping purposes. These highly detailed meshes are not suitable for deformation, animation, or real-time applications (Kalay, 2004). Therefore, real-time content and asset creators rely on DCC software to maintain micro and surface details through *texture mapping* and maintain object silhouette and macro details through the process of geometry *remeshing*.

5.1.3. Texture mapping

As previously stated, although modern DCC software can handle millions of polygons, this high density may not be suitable for interactive real-time virtual environments. The computational expense of heavy geometry was present since the beginning of computer graphics development (Kalay, 2004). The need for an efficient method to add macro and micro details to a surface necessitated the pioneering and advancement of texture mapping (Blinn & Blinn, 1978; Blinn & Newell, 1976; Catmull, 1974; Kalay, 2004).

Texture mapping is the process of mapping two-dimensional textures onto three-dimensional objects to simulate variation in surface texture, color, and bumps (Mitchell & McCullough, 1995). It is often used to simulate material surface textures (Bertol & Foell, 1997). Texture maps may be layered where different maps can have varying levels of transparency. This ability to layer maps allows for greater control over, macro and micro, details and variation when creating textures for the HFT model.

MODO comes with pre-installed high-quality material presets that simulate different types of materials and surfaces. For the development of the prototype, material presets allowed for the possibility of creating textures from scratch or building upon existing

ones out of the box. Mapping textures on non-rectilinear surfaces can be challenging where greater attention needs to be paid to texture scale, orientation, and perceptible repetition, especially when small textures are mapped onto large surfaces (Mitchell & McCullough, 1995).

Two types of texture maps were used for the HFT: image maps, which rely on textures from bitmap image files, and procedurally created texture maps. Each type comes with its advantages, challenges, and limitations.

For bitmap image textures, the problem is usually using real world textures to achieve photorealism without obvious seams or texture repetition (Darknell, 2016b). Most often, the creation and preparation of bitmap image textures require the use of photography and image processing software. Nevertheless, one advantage of bitmap based textures in MODO is that they may be displayed in the OpenGL viewport for a WYSIWYG workflow.

The advantage of procedural texture maps is that they are mathematically created at render-time; therefore, procedural textures have no seams and no fixed resolution, i.e., they can be scaled up or down at will. As a result, procedural textures cannot be displayed in the OpenGL viewport of MODO and therefore necessitate the time-consuming process of rendering and inspecting to arrive at the final texture map (Darknell, 2016b).

Image-based and procedural texture maps were used extensively to create texture maps and simulate variations for the models used in the final prototype. For example, a significant time was spent on recreating the texture maps for the fluted concrete walls. A total inclusive number of 25 image-based and procedural texture layers were used to simulate the color and surface variation, weathering, cracking, and surface cavities (Figure 5.5). Some procedural texturing methods consider surface concavity and convexity when applied onto a 3D object. Therefore, the use of procedural textures made it possible to define a single material that procedurally adapts to all fluted concrete walls without signs of seams and/or repetition.



Figure 5.5. Surface variation, weathering, cracking, and cavities.

5.1.4. Remeshing

It may be necessary to go through the process of *remeshing* or *mesh reduction* to maintain macro details and object silhouette with a relatively low-poly mesh. Remeshing, also known conventionally as retopologizing, is the modification or rebuilding of mesh sampling and connectivity to generate a new mesh (Alliez et al., 2002; Klein, Liebich, & Strasser, 1996). For game asset creation, remeshing usually means reducing the number of polygons in a mesh, i.e., mesh reduction. In general, to remesh a model is to create a relatively low-poly object by using a high-poly object as a guide. Remeshing may be done for multiple reasons: (1) to reduce rendering time; (2) to create meshes that can predictably adhere to deformation; (3) to improve viewport navigation and responsiveness when manipulating models; (4) to create real-time and game ready assets; (5) to correctly and predictably apply textures onto the surface; (6) to generate efficient UV maps. Remeshing in this research is used for reasons 4, 5, and 6. The outcome of the re-topology process is a relatively low-poly mesh that is efficient

and suitable for either texturing, deformation, animation, real-time interactivity, or all the above simultaneously.

Automated regeneration of meshes is possible (Bommes, Lempfer, & Kobbelt, 2011). Modern DCC packages, including MODO, may have automatic remeshing and mesh reduction capabilities. Otherwise *InstantMesh*, for example, is an open-source software which generates highly accurate and efficient low-poly meshes from high-poly meshes (Jakob, Tarini, Panozzo, & Sorkine-Hornung, 2015). However, there is often a need to manually remesh models to create optimized predictable mesh behavior under manipulation, deformation, and texture application. The importance of manual remeshing pushed most DCC software to include a set of tools for efficient retopology workflow.

A combination of mesh reduction methods, manual and automated, were used to optimize HFT geometric data for real-time VE. The number of polygons was brought to a minimum for all architectural elements, fixtures, and furniture. For example, polygons completely occluded by other objects were removed. By eliminating trivial geometry, it was possible to significantly reduce the overall number of polygons. For example, Figure 5.6 is a comparison of a piece of furniture where the high-poly model consists of 11,897 polygons and the low-poly counterpart consists of merely 360 polygons. Figure 5.7 is another example where the geometric definition of the ground reduced to only 130 polygons from 204,300 polygons.

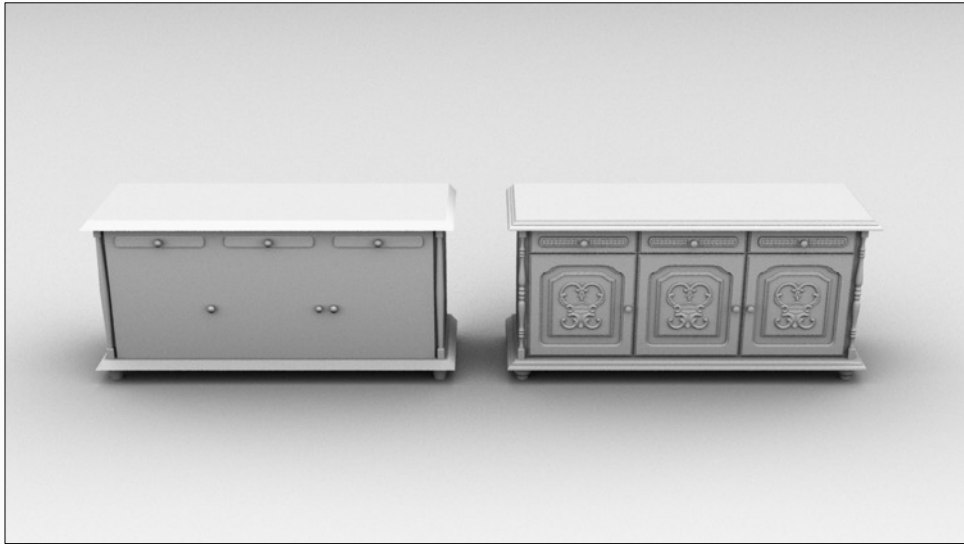


Figure 5.6. Low-poly (left) vs high-poly (right) piece of furniture.

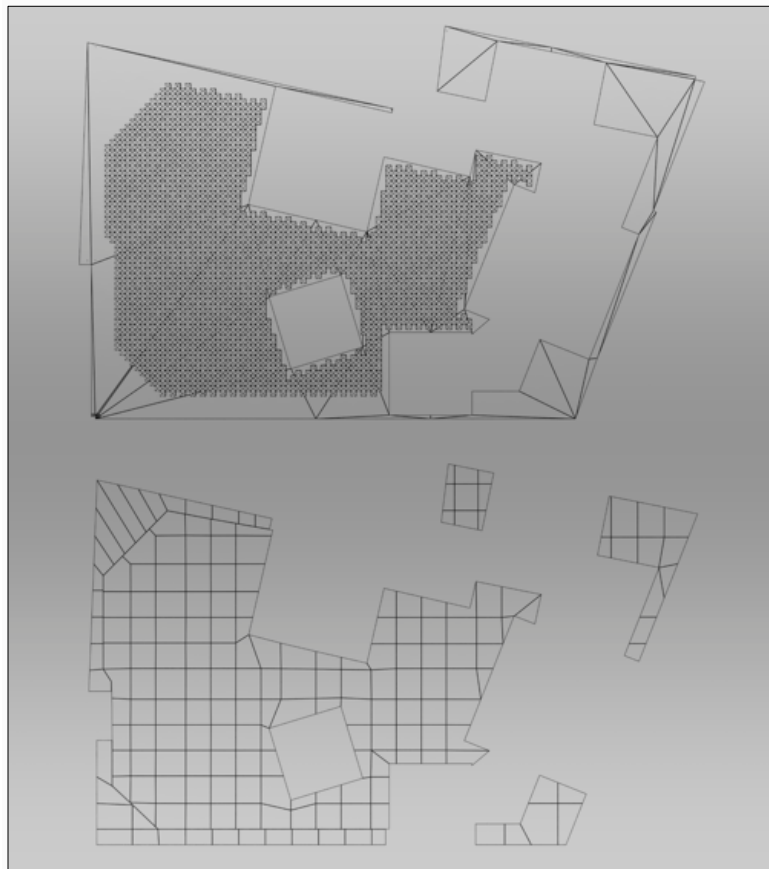


Figure 5.7. Low-poly (bottom) vs. high-poly (top) for the ground details associated with *DesignOption01*.

As can be seen in Figure 5.6, the efficiency of lesser polygon-count may diminish details. These details may be necessary to communicate design intent and/or to produce photorealistic visualizations. To preserve detail while using relatively low-poly models, there is a need to transfer details of a high-poly mesh onto the low-poly counterpart via a process known as appearance-preservation simplification, or *texture baking*. Figure 5.8 demonstrates the same models in Figure 5.6 where details are transferred from the high-poly model to the low-poly model via *texture baking*. Further details about *texture baking* are provided in subsequent sections in this chapter. Nevertheless, a prerequisite to texture baking is the creation of a high-quality UV map due to the reliance on many aspects of mesh representation (computation, color, normal, detail ...etc.) on the quality of a UV map (Zhang, Mischaikow, & Turk, 2005).

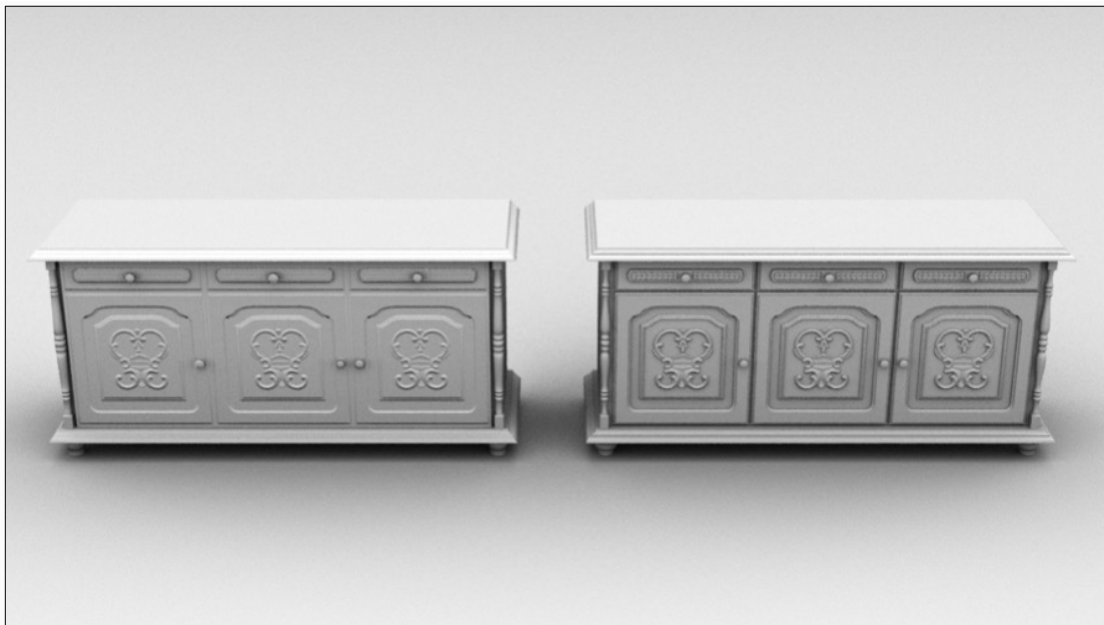


Figure 5.8. Low-poly (left) with texture baked details vs high-poly (right) piece of furniture. The low-poly model (left) uses the same low-poly mesh in Figure 5.6.

5.1.5. UV mapping

Essential to texture mapping and *texture baking* is the creation of an efficient UV map for the low-poly meshes. UV maps for all architectural elements, fixtures, and furniture of the HFT were generated. UV mapping is the conventional term in DCC and game engine software that references the computer graphics term, *surface parameterization*. Surface parameterization is the segmentation of three-dimensional meshes into flat, two-dimensional patches without overlaps (Zhang et al., 2005). Simply put, a UV map is a custom unwrapped two-dimensional representation of the usually volumetric three-dimensional mesh (Figure 5.9).

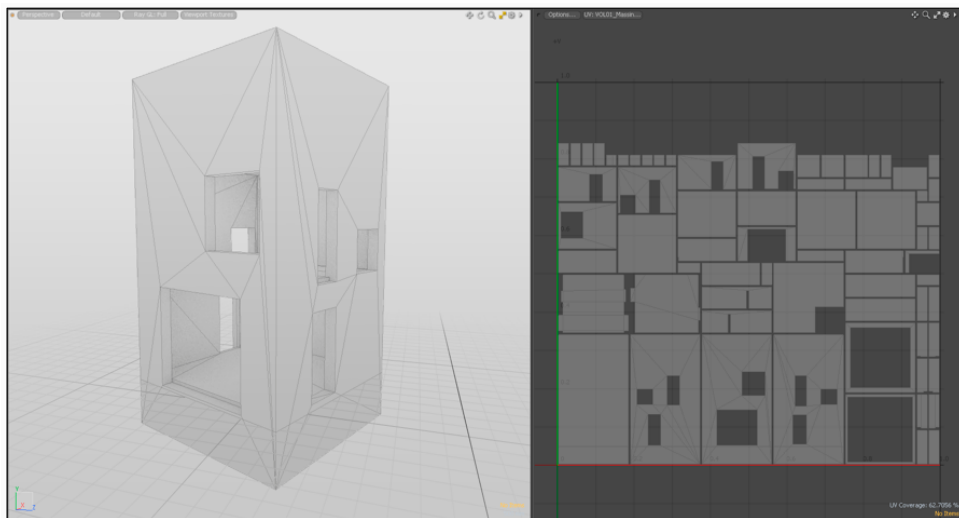


Figure 5.9. Sample UV map (right), of *box01* model (left) used in the PDR prototype.

The two-dimensional mesh representation allows for predictable detail and texture transference from the high-poly mesh to the low-poly mesh via texture baking. In fact, surface parameterization was introduced to computer graphics as a method for texture mapping (Sheffer, Praun, & Rose, 2007). Additionally, UV maps allow for efficient texture transference from DCC software to other DCC software and/or game engines. Guidelines and attributes that help make UV maps efficient for real-time assets were

followed (Darknell, 2016d; 2016e; McDermott, 2010). These guidelines include: minimizing UV seams, minimizing distortion, and maximizing objects in UV space.

5.1.6. Appearance-preservation via texture baking

Texture baking is the conventional term for a method of Appearance-preserving (Krishnamurthy & Levoy, 1996). Texture baking is the process of recording texture, lighting, or cavities into image files that may then be used as texture maps. Amongst its different utilities, texture baking facilitates the creation of a single texture image file for an attribute of several composite materials and texture layers (Figure 5.10). It also facilitates the transfer details from a high-poly mesh to a low-poly mesh via normal maps (Figure 5.11).

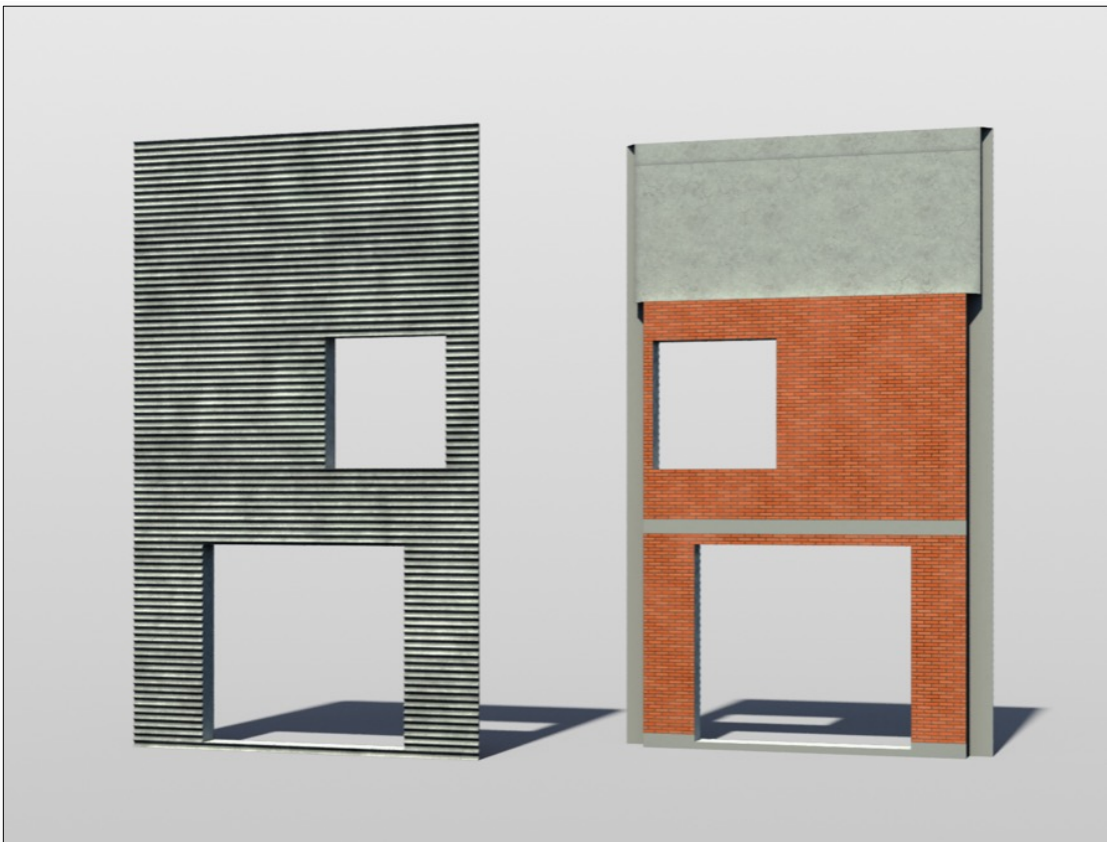


Figure 5.10. Texture baking facilitates the use of a single map to define different materials. Here, the surface color attributes are baked into a single texture albedo map.



Figure 5.11. Normal texture baking facilitates the transference of surface qualities from high-poly models (right) to low-poly models (left).

For the prototype, texture baking was extensively used to transfer defined textural qualities from MODO to the game engine. For example, each *box* in the HFT consists of four enclosing poured on site concrete walls. These walls are finished with locally-sourced bricks on the interior. Bamboo formwork was used for the exterior surfaces of the concrete (VTN Architects, 2014). The use of bamboo gave the concrete a subtle, perceptive variation in color and texture. Likewise, a variation of color and texture may also be noted by inspecting photographs of the built HFT. Therefore, a deliberate attempt was made to capture and simulate the subtle surface qualities via texture maps.

Every wall in the HFT model was made of a single geometric object and an associated UV map that contains all wall's surfaces. Texture baking and the UV mapping were used to compile all interior and exterior material representation into a group of 8k PBS-ready texture maps per wall. For each wall, at least three texture maps were baked: an *albedo map* which holds diffuse color information (Figure 5.12); a *normal map* which holds *surface normal* deviations (Figure 5.13); and an occlusion map

which helps further define surface cavities (Figure 5.14) (Körner, 2015). The same process was conducted for all other elements in the HFT.

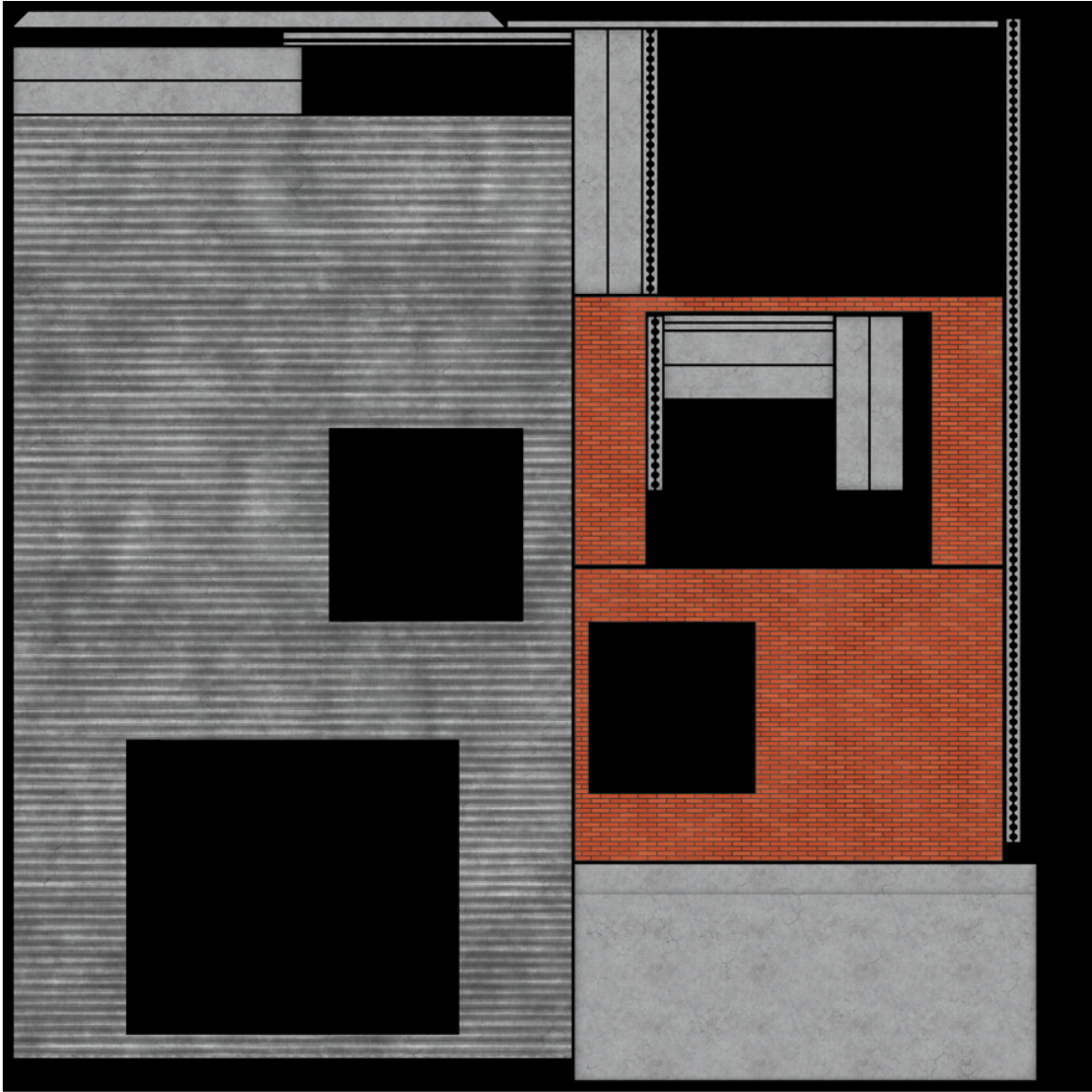


Figure 5.12. Albedo map sample from *box01*.

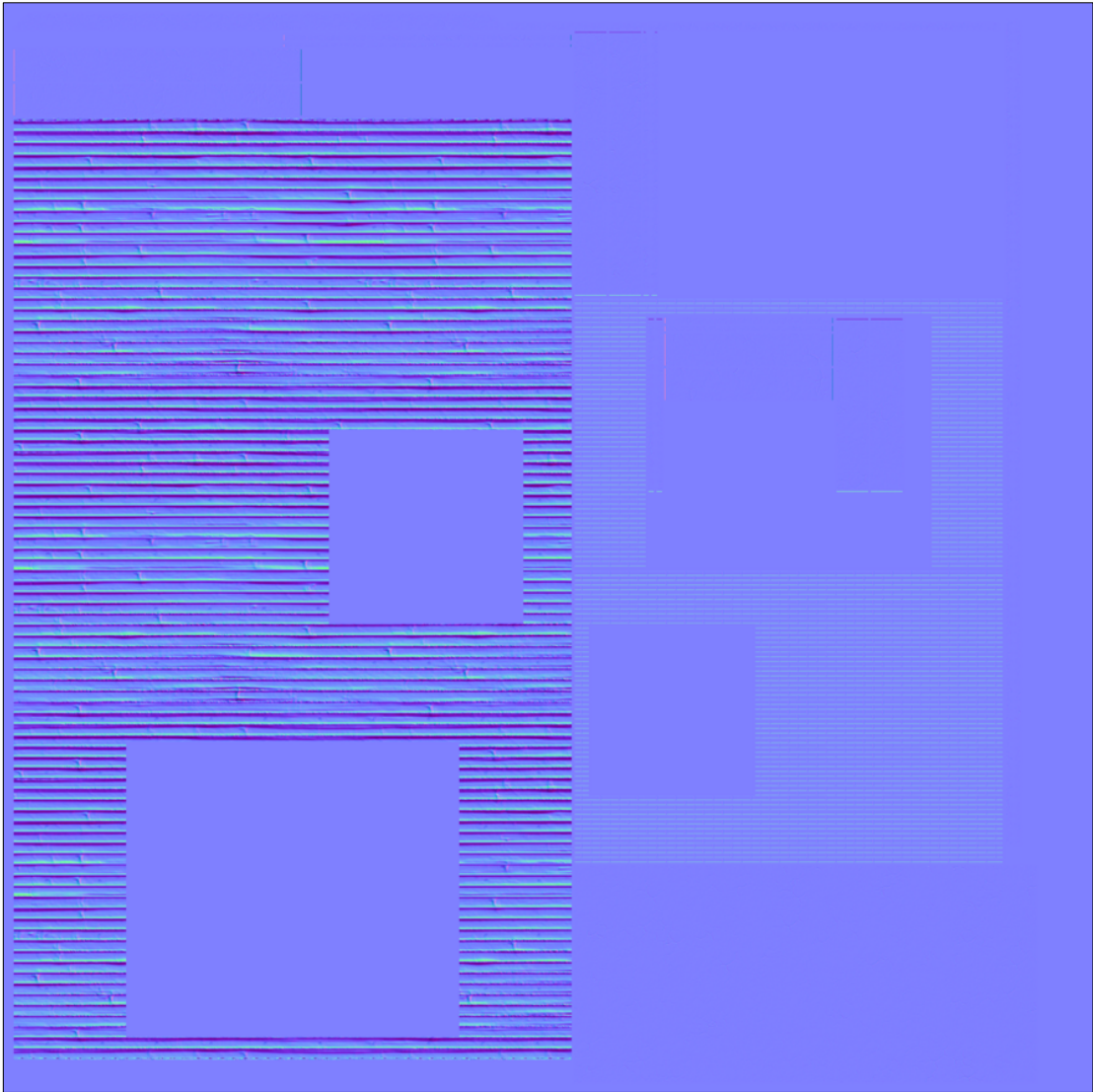


Figure 5.13. Normal map sample from *box01*.

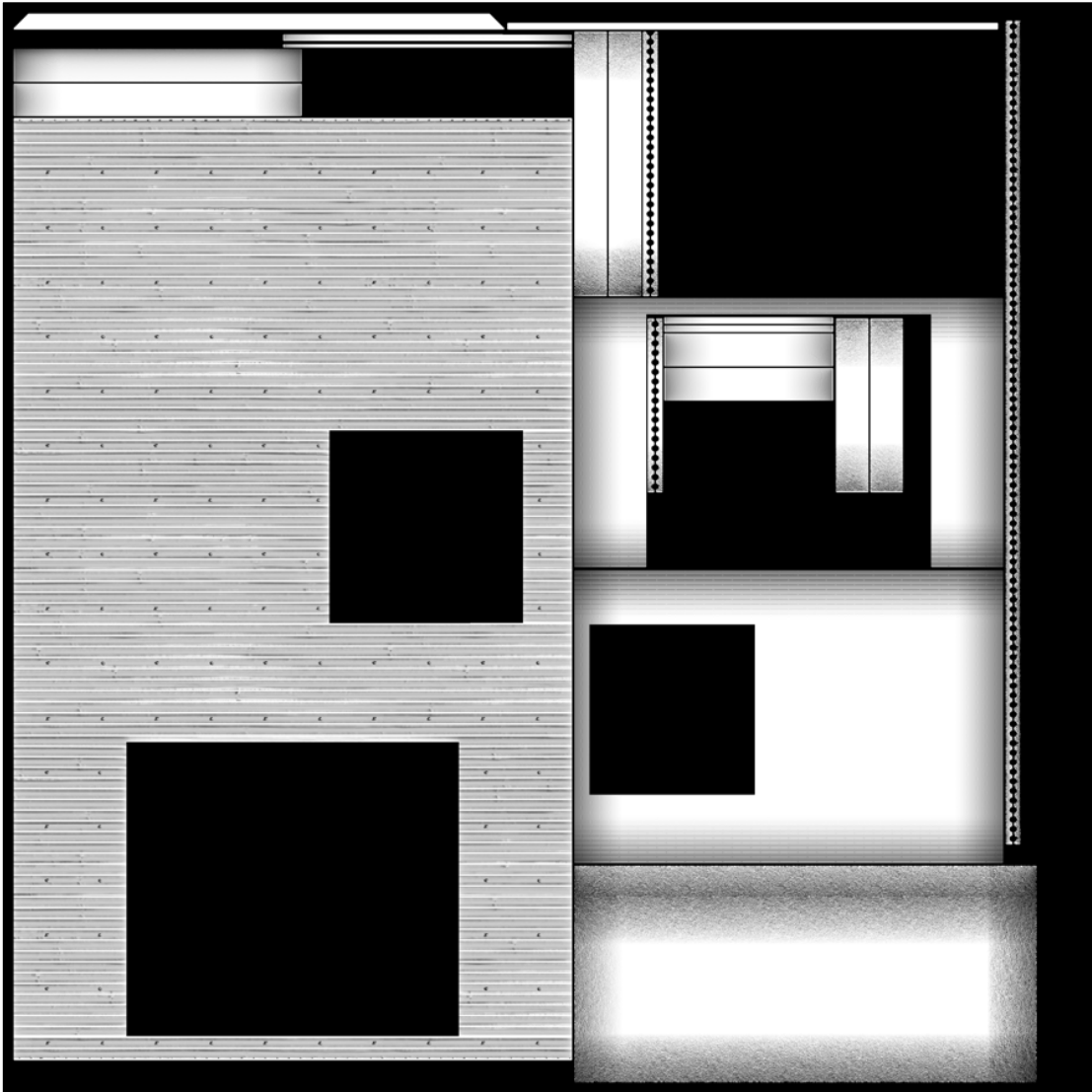


Figure 5.14. Occlusion map sample from *box01*.

While other elements in the HFT went through a similar process, one instance required further optimization. As previously mentioned, the ground of the courtyard of the house is made of perforated brick cement which allows for grass to grow between the bricks and inside their perforations (VTN Architects, 2014). This quality is very striking in the photographs which made it a necessary element to be replicated in the VE. Through a semi-automated process that relies on both Rhino/GH and MODO, the ground plane was procedurally populated with bricks of subtle variable sizes, rotations, and

colors. These surface details were baked onto five texture maps; *albedo*; *normal*; *occlusion*; an *alpha map* for clipping brick parts where grass may grow (Figure 5.15); and a *height/parallax map* used for rendering surfaces with large, and possibly self-occluding, protrusions (Figure 5.16) (“Unity - Manual: Heightmap,” 2017). Figure 5.17 shows the results of the texture baking process of the ground plane in one of the design options.

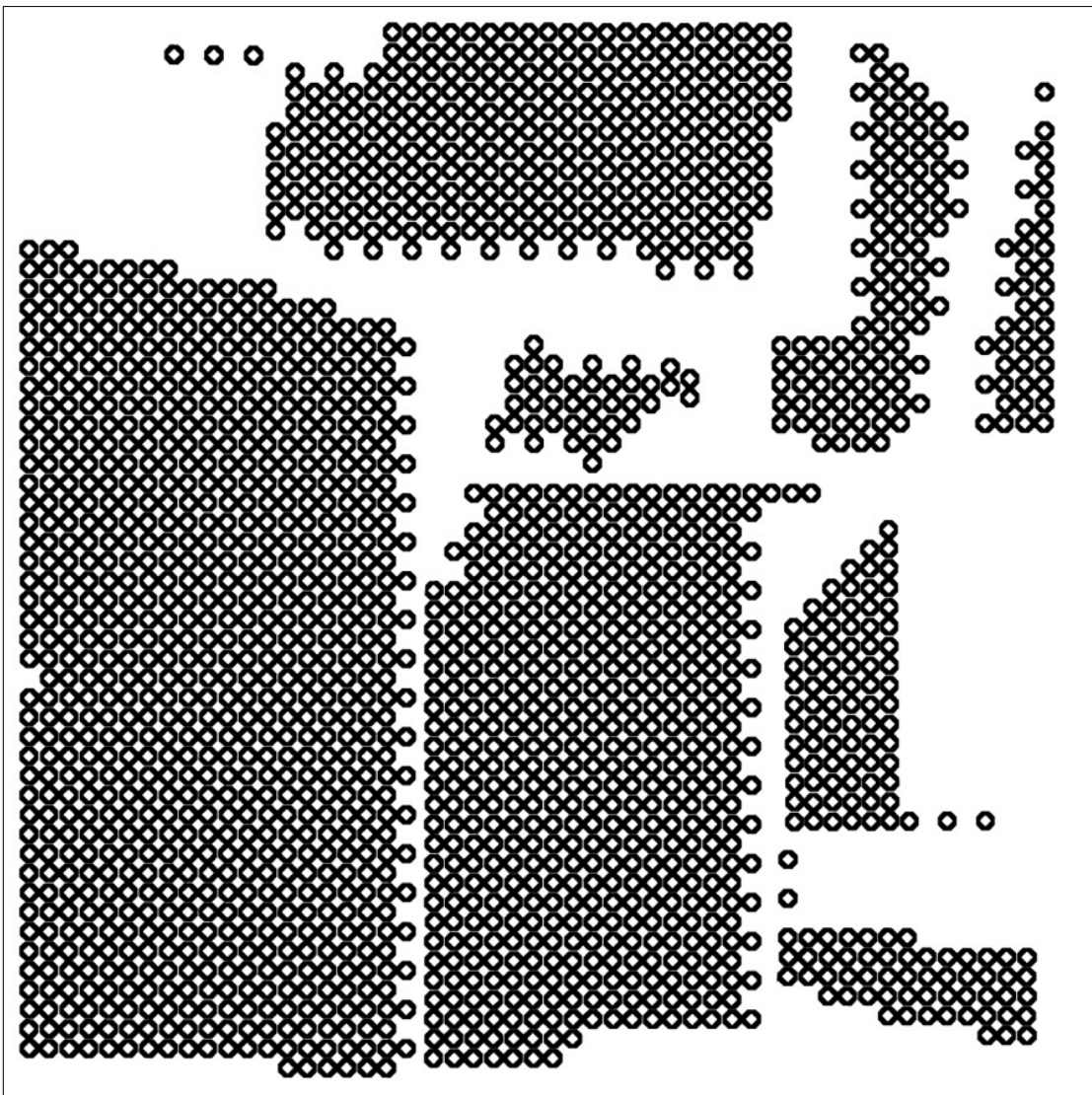


Figure 5.15. Alpha map where the white pixels indicate where grass may grow.

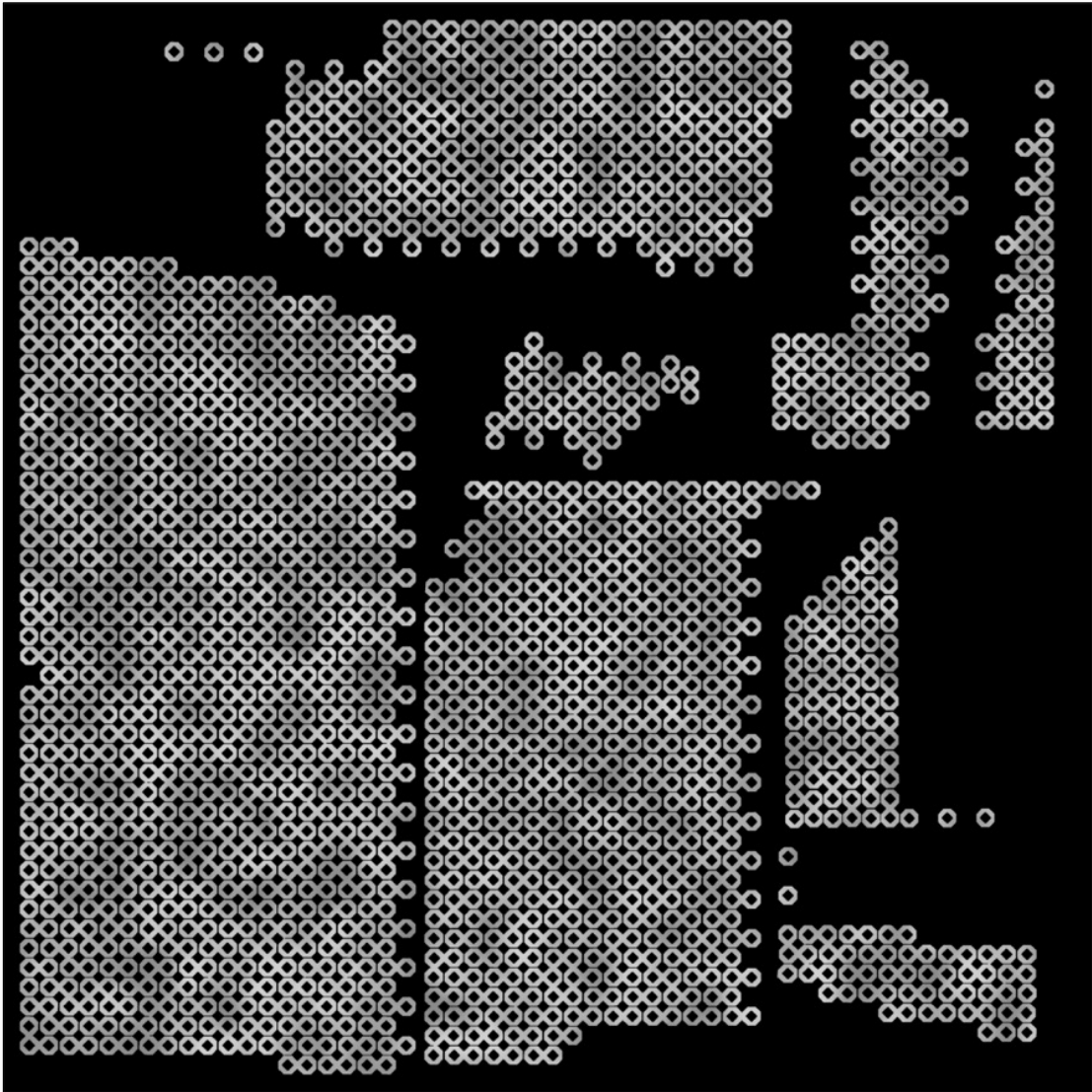


Figure 5.16. Height/parallax map used for rendering surfaces with large, and possibly self-occluding, protrusions.



Figure 5.17. Results of the texture baking process of the ground plane. Note that the geometry for the ground is made of a series of coplanar flat polygons. Perforations in the ground are created via color inverting the alpha map for the grass in Figure 5.15.

5.1.7. *Simulation baking*

Solar radiation, UDI, and glare simulation results from GH are per-vertex colored meshes, i.e., the color representations in the meshes are embedded in the vertices data structure rather than in texture maps. FBX, the preferred game engines asset format, may hold per-vertex color data. Nevertheless, Rhino does not support embedding per-vertex color data in the exported FBX meshes. Currently, Rhino supports the exporting of per-vertex color data only via VRML format. Thus, all meshes that require the retention of per-vertex color data were exported using the VRML format. These meshes were then brought into 3DMax to be exported as FBX files. FBX files exported from 3DMax retain per-vertex color data.

Although game engines may render per-vertex color meshes embedded in FBX files, the results of some simulations may be high-poly meshes that are not suitable for real-time interaction. For example, the solar radiation mesh of the *Original Design Option* is made of approximately 30,000 polygons (Figure 5.18). Through a process of retopology,

the number of polygons was reduced to 2100 polygons. The per-vertex color data for the *Original Design Option* were baked onto a texture map to accurately transfer color data from the high-poly mesh to the low-poly counterpart (Figure 5.19). A similar process was conducted for the UDI and *estimated annual glare potential* analysis where the number of polygons was reduced from 1,196 polygons to merely 10 polygons for each analysis.

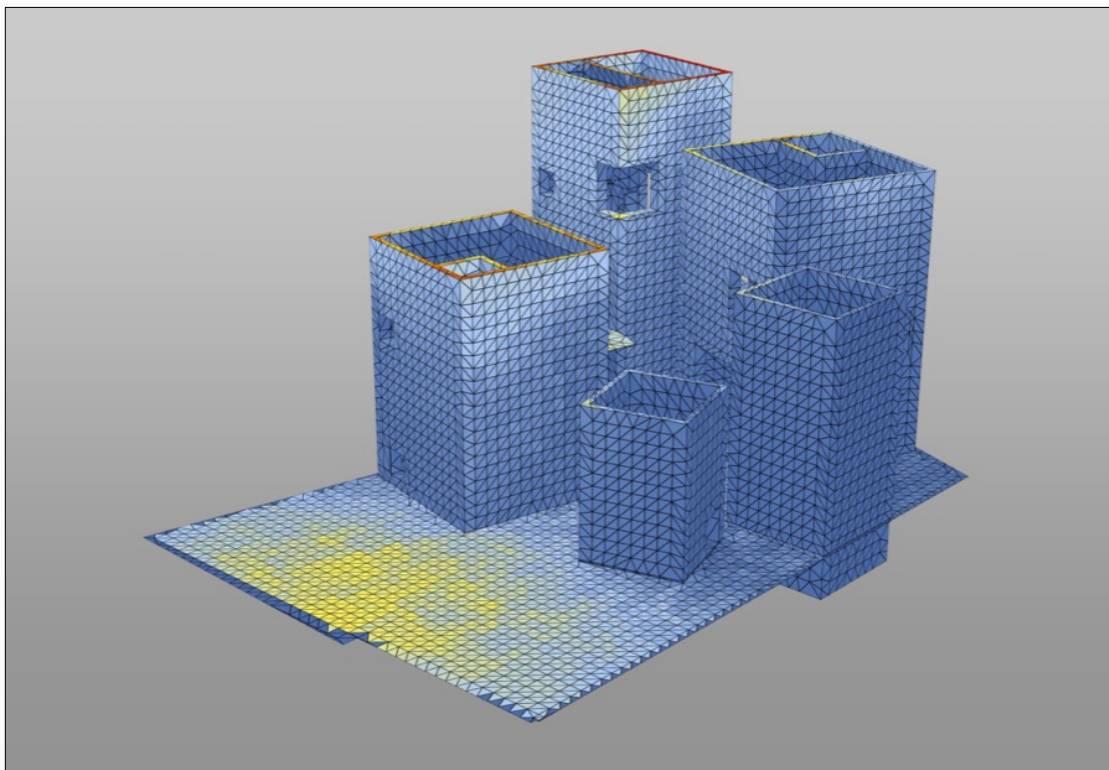


Figure 5.18. High-poly per-vertex color mesh (approximately 30k polys). Note the black lines representing polygon edges.

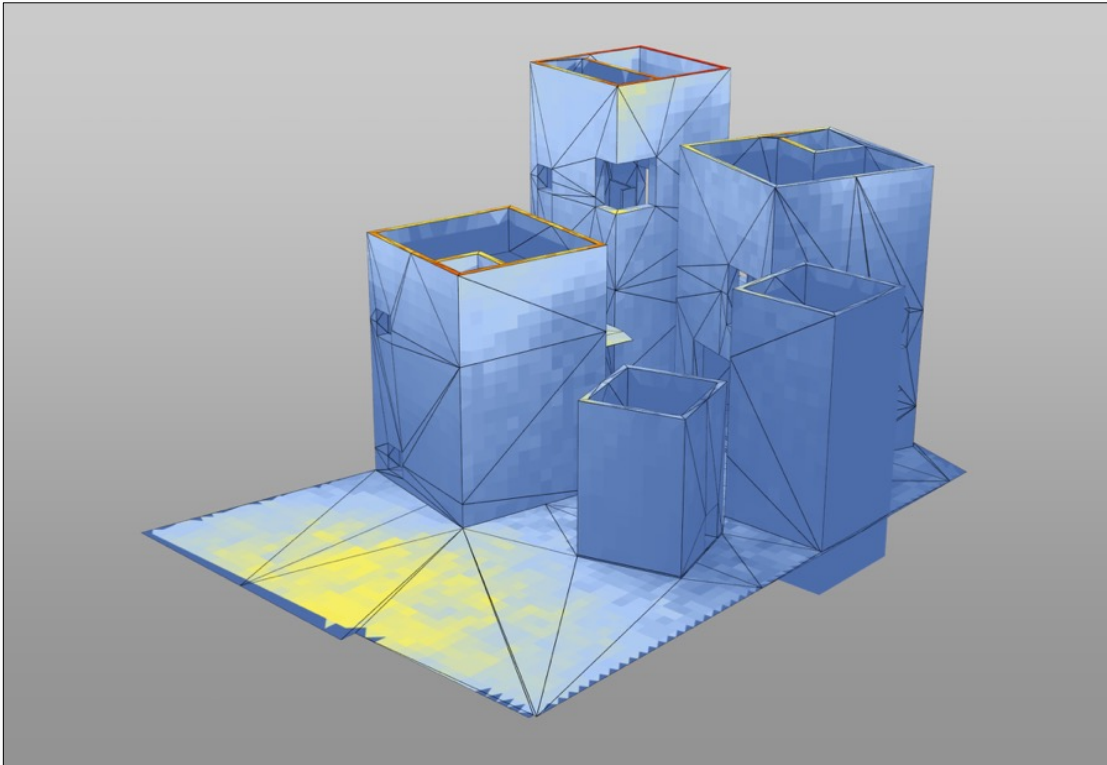


Figure 5.19. Texture baked solar analysis onto a low-poly mesh (approximately 2K polys).

5.1.8. Object parameters

For a design review, not all parametric elements or properties are useful or needed. Using the initially created BIM model, a custom script was set up in Dynamo to export the parametric properties of elements specified by the user. The script iterates through all specified elements to compile the parameters in alphabetical order. The list of parameters consists of material properties if available, and object parameters. For every element, the list of parameters was exported from Revit into a separate text file (parameter file) that will be imported into Unity later on. (Altabtabai & Yan, 2015).

5.2. Parametric Design Review (PDR) Interface Using a Game Engine

Unity 5.5 game engine was used to create an interface within which we may qualitatively and quantitatively evaluate the ten optimized design options. All data generated and processed up to this point were transferred and stored in the Unity project.

This data includes geometry, textures files, image files, and text files. Once the necessary data were imported into Unity, the models were situated, textures were applied, collision properties defined, and different custom scripts were attached to objects to allow for interactivity. All objects were assigned different layers to allow for better data management.

Imported models may fit into three categories: conceptual models, phenomenological models, and analytical models. The conceptual models were low detail massing models that consist of: a model of the five concrete *boxes* (Figure 5.20); a model of the context (Figure 5.21); ten models of bridges' where each model corresponds to one of the optimized design options (Figure 5.22); and ten models of the ground each of which corresponds to an optimized design option (Figure 5.22).

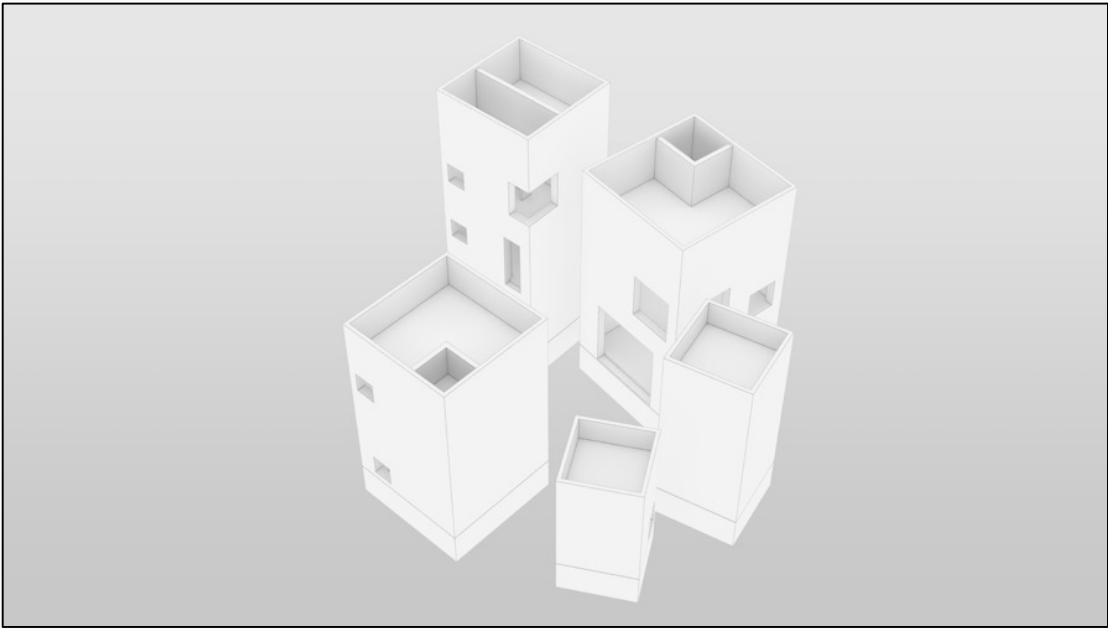


Figure 5.20. Conceptual model of the five concrete *boxes*.

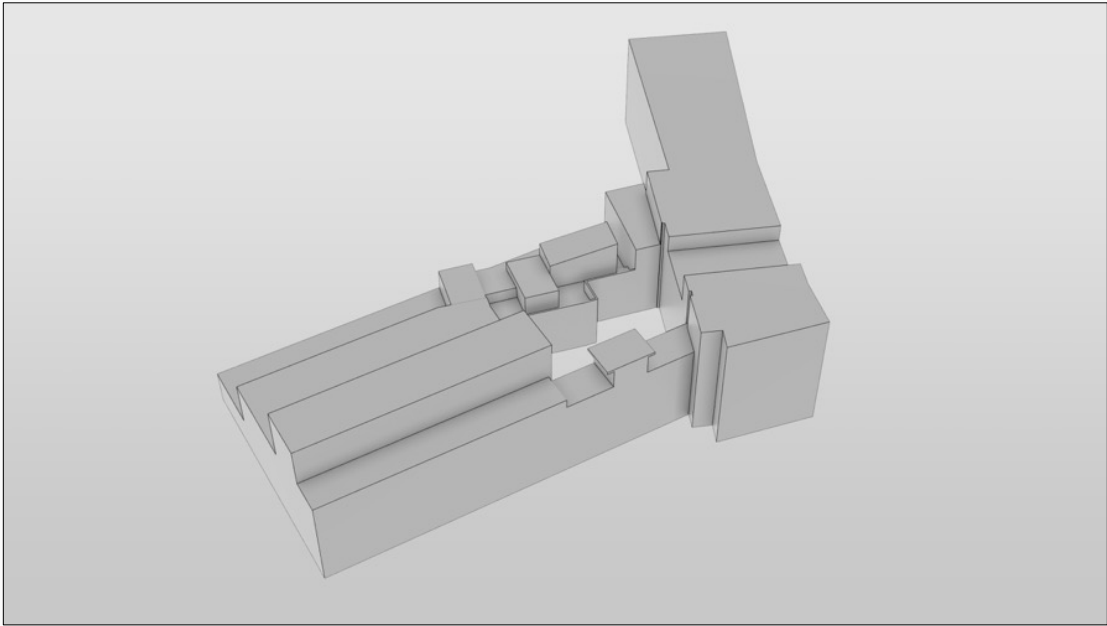


Figure 5.21. Conceptual context massing model.

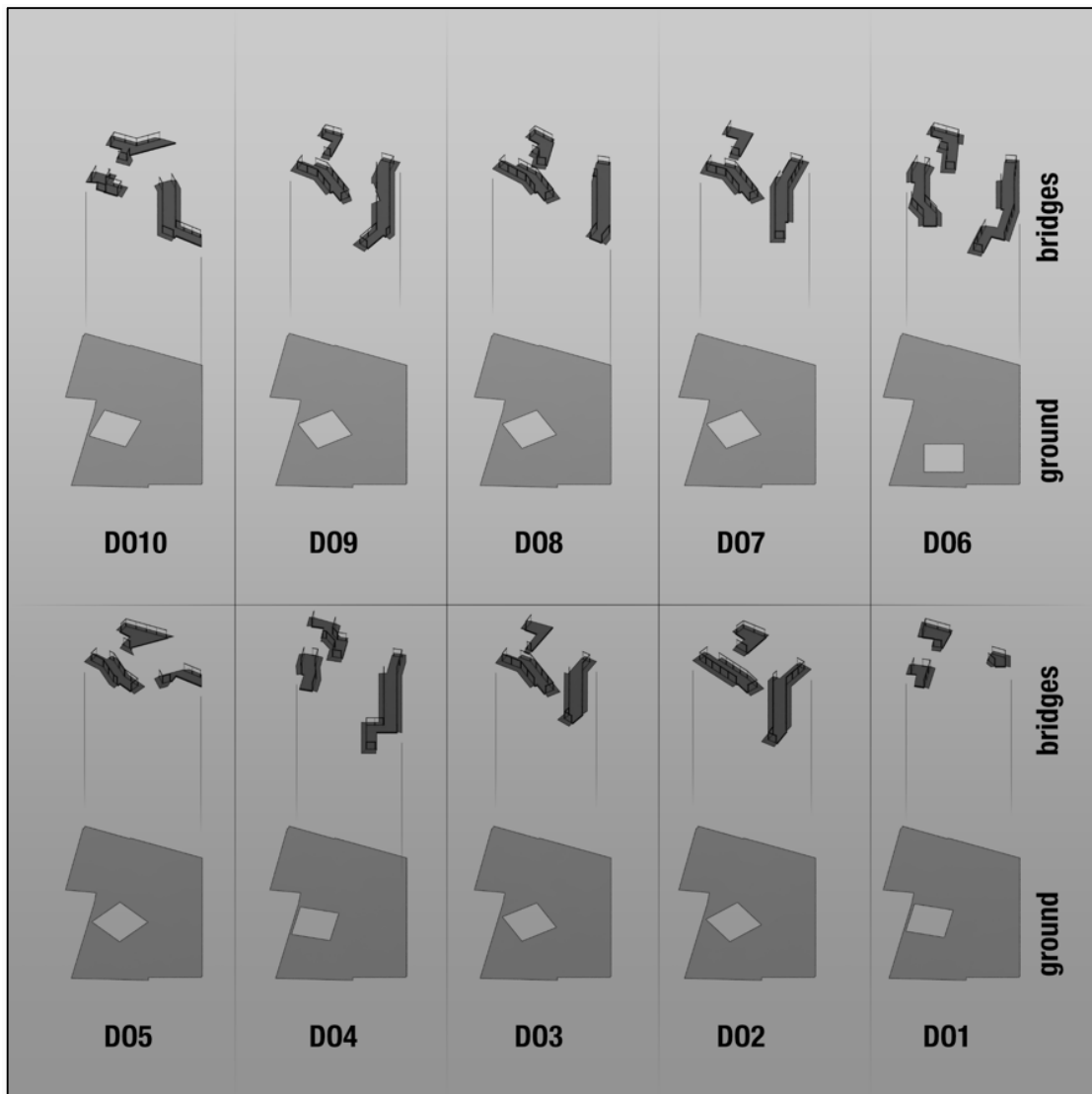


Figure 5.22. Ten conceptual models of bridges' and ten conceptual models of the ground. Each model corresponds to one of the optimized design options.

The phenomenological models consist of: five fully textured and detailed HFT *boxes* and all objects within, e.g., furniture, fixtures, and MEP (Figure 5.23 and Figure 5.24); ten fully textured and detailed bridges' models each of which corresponds to one of the ten optimal options (Figure 5.25); and ten fully textured ground and concrete corridor models each of which corresponds to one of the ten optimal options (Figure 5.25). Note that the five boxes model is the same for all design options. The model containing the

five boxes was duplicated ten times inside the game engine where each duplicate instance was moved and rotated to adhere to one of the optimized design options.

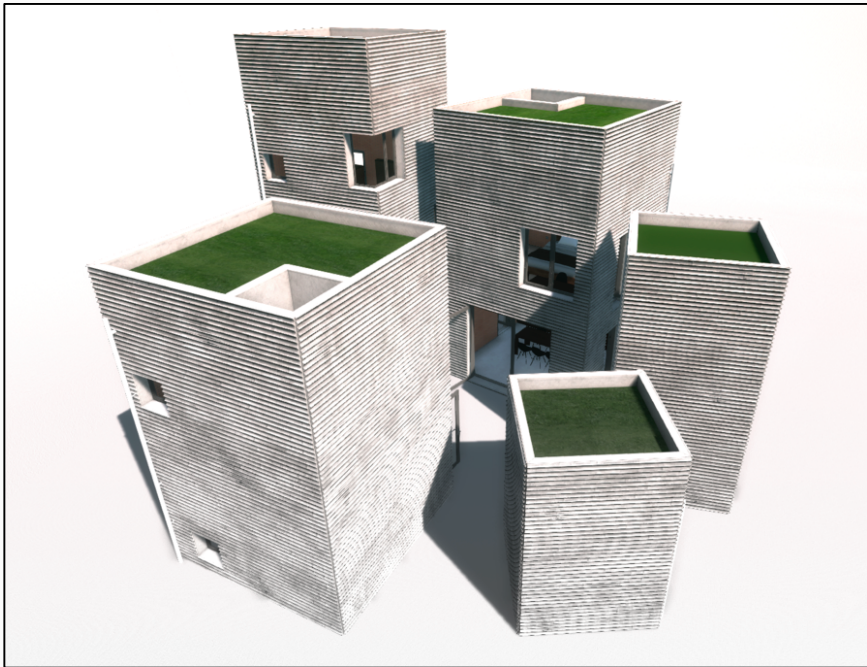


Figure 5.23. The five HFT concrete *boxes* used in all phenomenological models.



Figure 5.24. The interior of the fully textured *box01*. Note the inclusion of details such as furniture, light fixtures, and light switches.

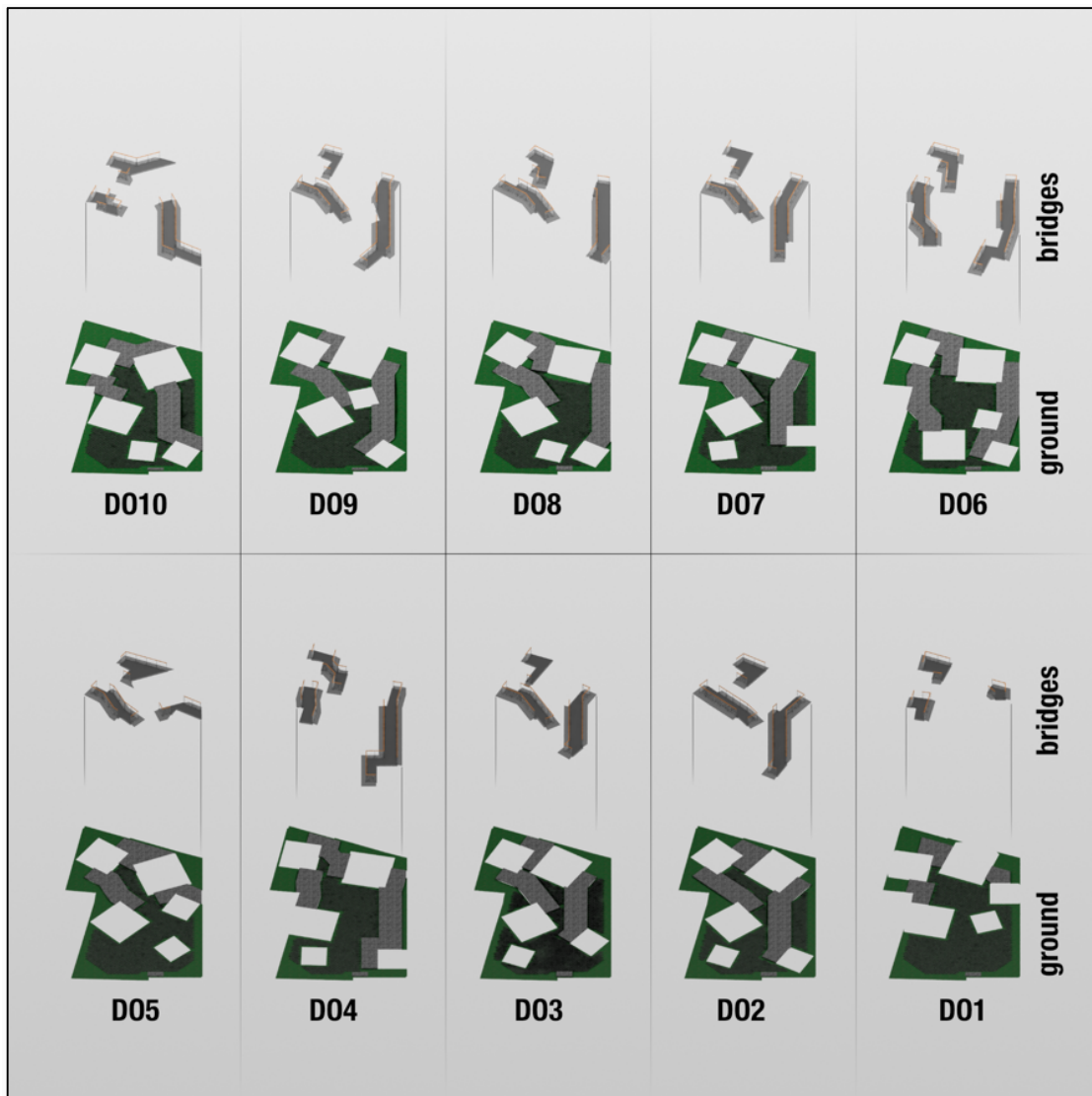


Figure 5.25. Ten fully textured ground and ten fully textured bridges' models each of which corresponds to one optimized design solution.

The analytical models (Figure 5.26) include: ten meshes of simulation results for solar radiation each of which corresponds to one of the ten optimal design options; ten meshes for UDI sensor data each of which corresponds to one of the ten optimal design options; and ten meshes for the *estimated annual glare potential (AGP)* sensor data each of which corresponds to one of the ten optimal design options.

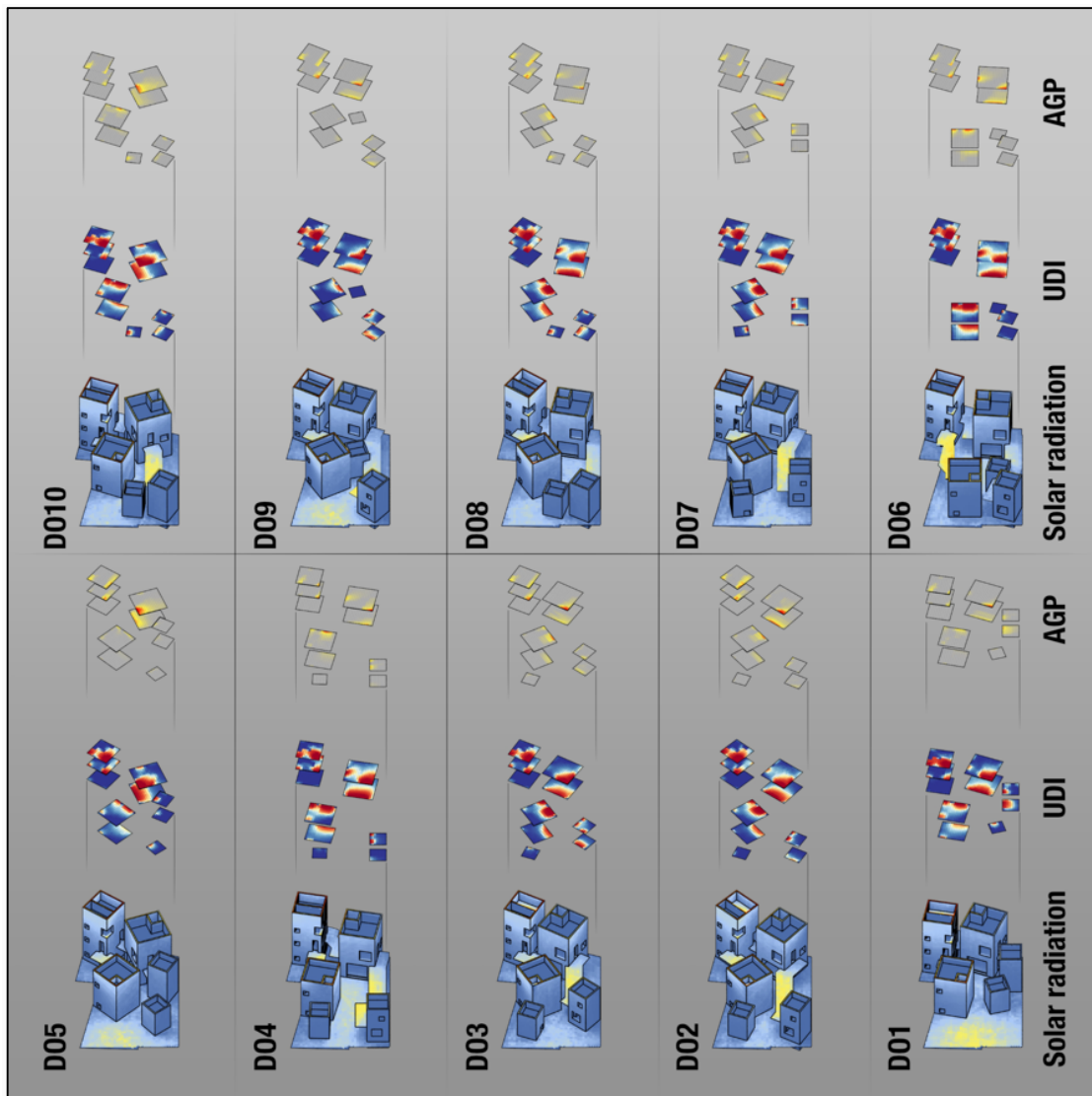


Figure 5.26. Ten solar radiation models, ten UDI results models, and ten AGP results models. Each model corresponds to one of the ten optimized design options.

I will attempt to describe the finished proposed interface prototype before explaining how all the imported data were used to create the PDR framework in Unity. The creation of the prototype was not done linearly. Rather, it was based on a series of trials and errors. Additionally, envisioned functionality dictated how and why the framework for the PDR interface was designed in such a manner. Therefore, it may be more appropriate to explain the outcome before delving into how the data were structured to arrive at the

result. The following discussion is based on the lists of theoretical and feature specifications for PDR provided in *Chapter 2*.

5.2.1. PDR interface description

The interface is divided into two main categories, the *main viewport* and a series of *support viewports* (Figure 5.27). The main viewport contains floating support viewports such as pop-up windows or other visualizations necessary for the current user's navigational or query tasks. Support viewports are customizable where the designer may choose relevant information and amongst different visualization methods and media for the design review. Visualization methods and media for the support viewports may, for example, be an image, a model, or analytical graphs.

The underlying assumption for the interface is that the screen space is unlimited. Therefore, the user is not confined by the size of desktop or laptop monitors, but rather by the number of available high-resolution projectors and large TV displays. Although the prototype is demonstrated by using a two-display scenario, *Display01* for the exclusive use of the main viewport and *display02* for support viewports, it is possible to use more than two displays for additional support viewports. Furthermore, the number of support viewports and their layout may also be customizable.

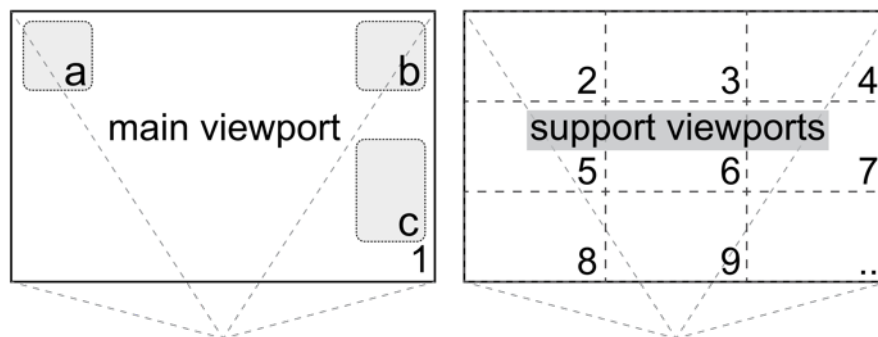


Figure 5.27: Main viewport 1, customizable support viewports 2-9, and floating support viewports a, b, and c.

Main viewport (Display01)

The *main viewport* may toggle between two evaluation modes: (I) *dashboard evaluation mode* and; (II) *navigation evaluation mode*. The *dashboard evaluation mode* gives an overall geometric and non-geometric description of the architectural project (Figure 5.28). It allows for the review of the quantitative performances and formal variations of multiple design options. The *navigation evaluation mode*, on the other hand, takes conventional interactive walk-through methods to a new level (Figure 5.29). It includes the ability to toggle amongst diverse types of representation to qualitatively and quantitatively inspect formal, phenomenological, and analytical aspects of a design option. It also allows for the display of simulation-based analysis spatially within the screen of the main viewport. The transition between *dashboard evaluation* and *navigation evaluation modes* enables the scrutiny of design options from different points of view. The following is a detailed description of two evaluation modes.

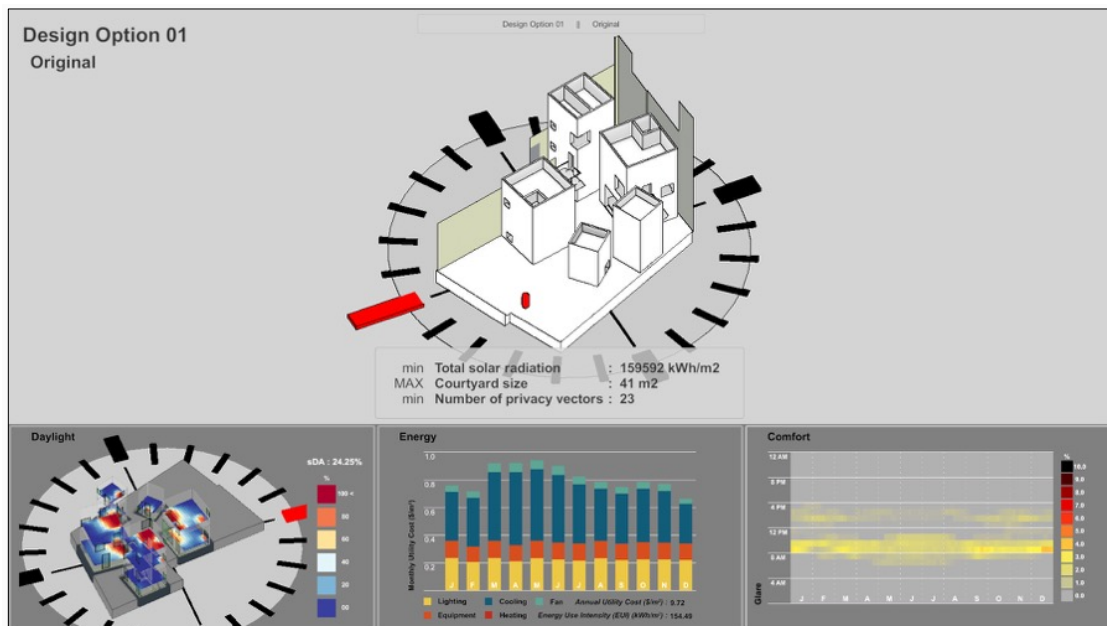


Figure 5.28. *Dashboard evaluation mode.*



Figure 5.29. Navigation evaluation mode.

Dashboard evaluation mode

The startup of the main viewport automatically initiates the *dashboard evaluation mode* where one may quantitatively evaluate the ten optimized design options (Figure 5.30). The dashboard is composed of two parts: (1) design option description; and (2) design option performance.

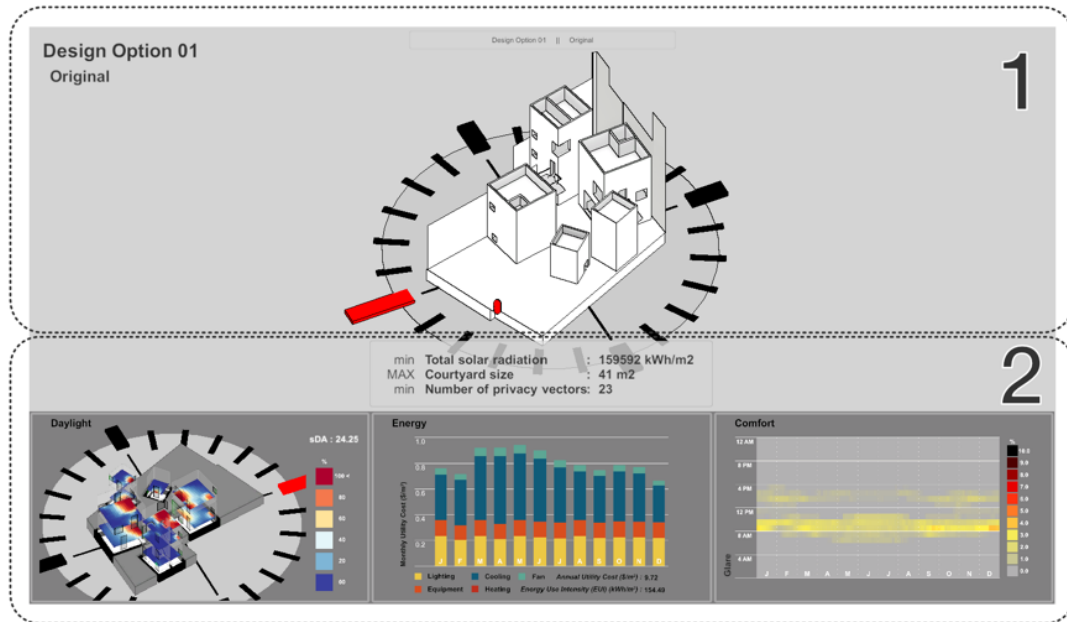


Figure 5.30. *Dashboard evaluation mode* composed of two parts: (1) design option description; and (2) design option performance.

The *design option description* part of the *dashboard evaluation mode* contains: (A) textual; (B) geometric massing model and contextual information of the original design option. The textual information reports the design option iteration and a brief description (Figure 5.31 - A). The massing model is represented via an axonometric projection drawing of the design option and the surrounding buildings (Figure 5.31 - B). The user may rotate the camera around the massing model when self-occlusion amongst the concrete *boxes* becomes a problem (Figure 5.32). The massing model is superimposed on the contextual compass that indicates the north direction for the project.

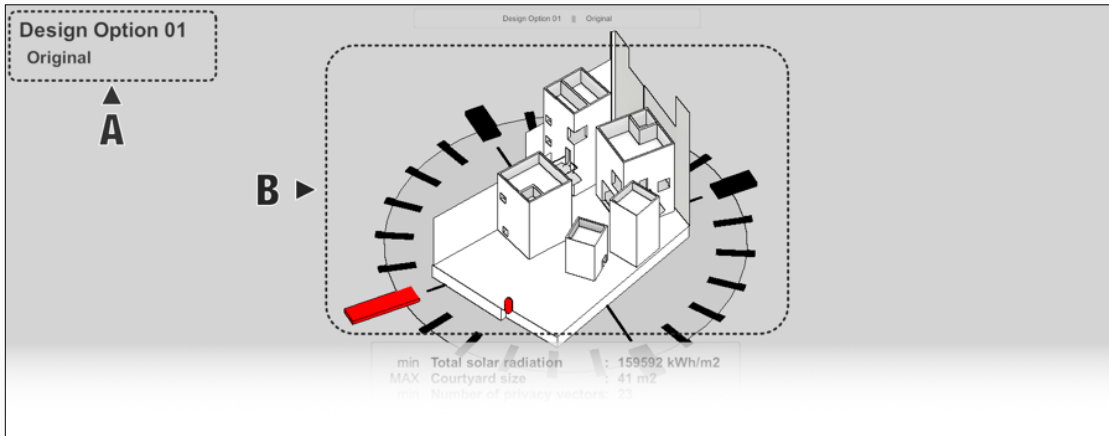


Figure 5.31. Design option description section of the dashboard evaluation mode. (A) textual information and (B) massing and contextual information.

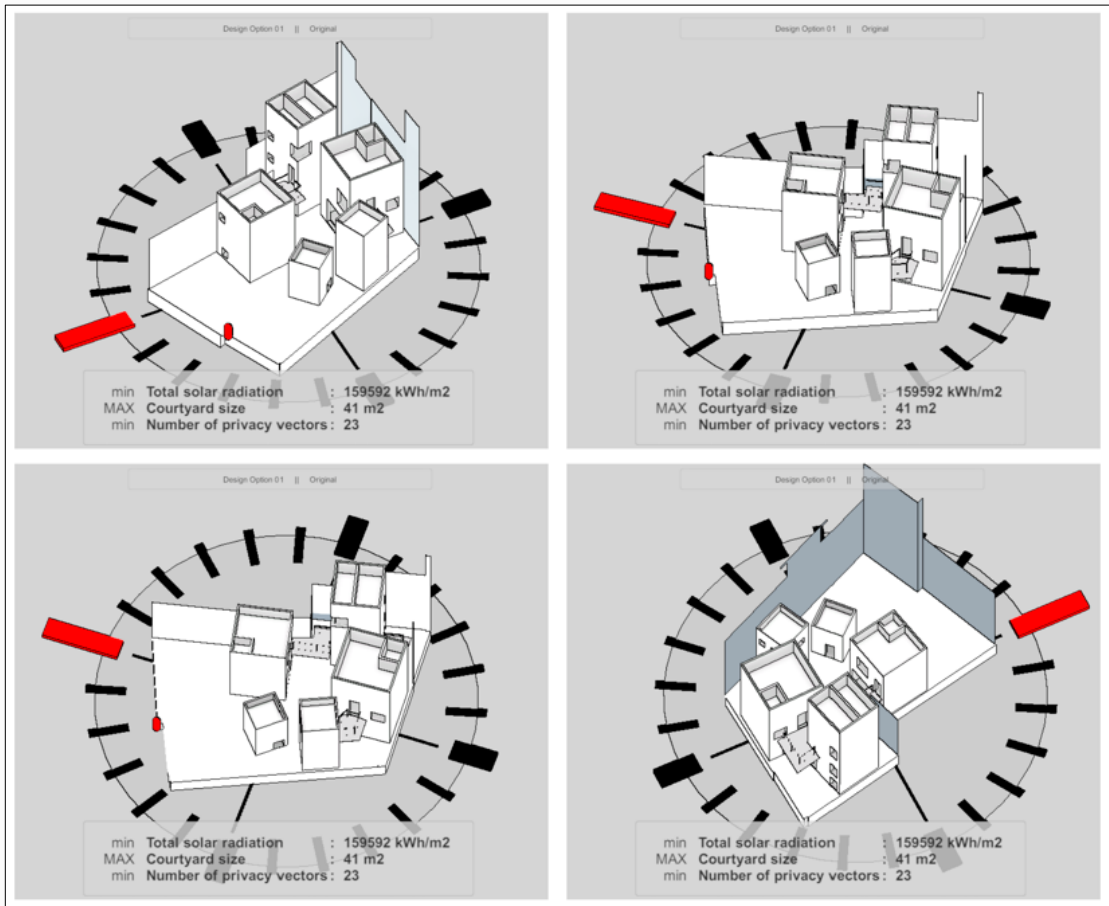


Figure 5.32. Samples of rotated axonometric model.

To further elaborate, the axonometric massing drawing provides a simplified representation of the five *boxes*, the user represented as a red capsule, the courtyard, and the immediate surfaces of surrounding buildings. All details are excluded from this visualization method including: all objects such as fixtures, furniture, doors, windows, and vegetation; representation of surface qualities such as shade, shadow, texture, and color; and detailed geometric conditions, such as the fluted exterior concrete walls of each *box*. The focus is thus on the solid enclosure of the *boxes*, their fenestrations, the interstitial space amongst the *boxes*, and the relationship between the *boxes* and site. The location of the user in the space may be indicated by the red capsule if the user is outside the volumes, i.e., in the courtyard. Alternatively, each *box* displays a visual indicator that reports when the user may be inside the *box*'s perimeter (Figure 5.33).

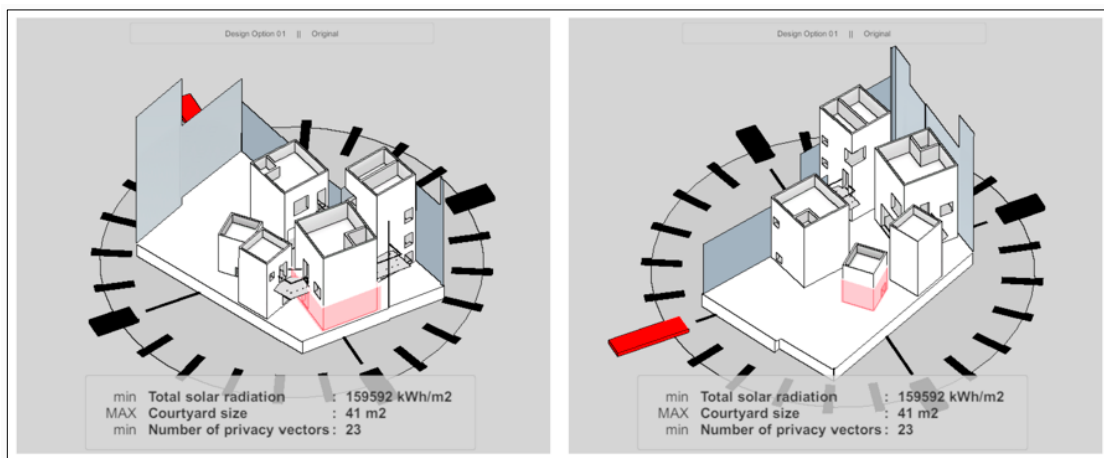


Figure 5.33. Indication of user's spatial location when the user, for example, occupies *box01* (left) or occupies *box04* (right).

The *design option performance* section of the dashboard consists of two parts (Figure 5.34). On the one hand, it reports the design option simulation results conducted for MOO (Figure 5.34 - C). On the other hand (Figure 5.34 - D), are reports of the three daylight performance categories based on published suggestions by Reinhart (2014).

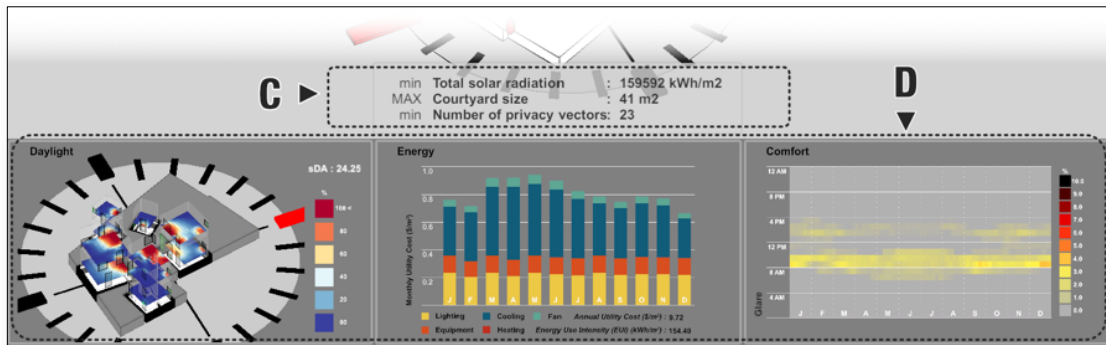


Figure 5.34. Design option performance section of the dashboard evaluation mode. (C) MOO simulation results and (D) reports of daylight performance categories.

The optimization results highlight the three simulations used during the MOO process. The first column starting from the left, reports the objective of the criteria, i.e., whether the goal is to minimize/maximize the results. The middle column describes the criteria, e.g., solar radiation, courtyard size, or number of privacy vectors. To the far right are the reported criteria performances from simulations computed for MOO.

Below the optimization results are the three performance categories which report the simulation results for *daylight availability*, *energy*, and *comfort* of the selected design option. More than one metric may be reported for each category. For example, two metrics are reported for daylight availability, three metrics for energy, and single metric for comfort. For the category of *daylight availability*, the dashboard reports sDA and UDI. For the category of *energy*, the dashboard reports EUI, Annual Utility Cost, and Monthly Utility Cost. Finally, for the category of *comfort*, the dashboard reports the *estimated annual glare potential*. Except for UDI, all metrics in the three performance categories rely on graphs and numerical representations to communicate the information.

The representation used to report UDI analysis in the daylight availability category relies on turntable animation as a technique to communicate UDI simulation results. The turntable view is used by computer graphics artists to demonstrate 3D models from different vantage points and/or under different lighting conditions. Figure 5.35 is a series of key-frames from a turntable sample. The inclusion of the turntable method is meant to highlight the possibility of a dashboard that may contain *automated dynamic*

representations, rather than relying solely on the display of graphs and numerical figures. It is also meant to provide visual access to the analysis from different vantage points in case self-occlusion becomes a challenge.

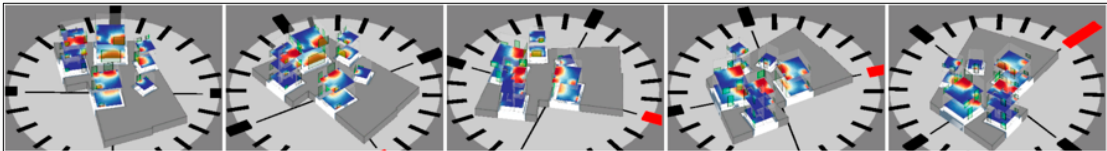


Figure 5.35. UDI analysis turntable visualization.

Design option morphology

A significant feature of the *dashboard evaluation mode* is the addition of animation-based methods to indicate the morphology of the HFT *boxes* from one design option to another. When a design option is selected, the *boxes* translate and rotate to express the change from the current design option to the next design option. Three visual vectors per *box* are displayed to assist the viewers in comprehending the *boxes*' transformations. For each *box*, a single vector is provided to indicate the direction and amplitude of the translation, and two vectors to indicate the direction and amplitude of rotation (Figure 5.36). The inclusion of this feature assumes that one may better comprehend the formal modification from one design option to another via the gradual animated translation and rotation of the *boxes* and the assisting visual vectors. It is worth noting that in comparison, the change in dashboard panels is rather abrupt. The only exception is the daylight availability category which uses similar animation-based techniques to indicate *boxes* transformations amongst design options.

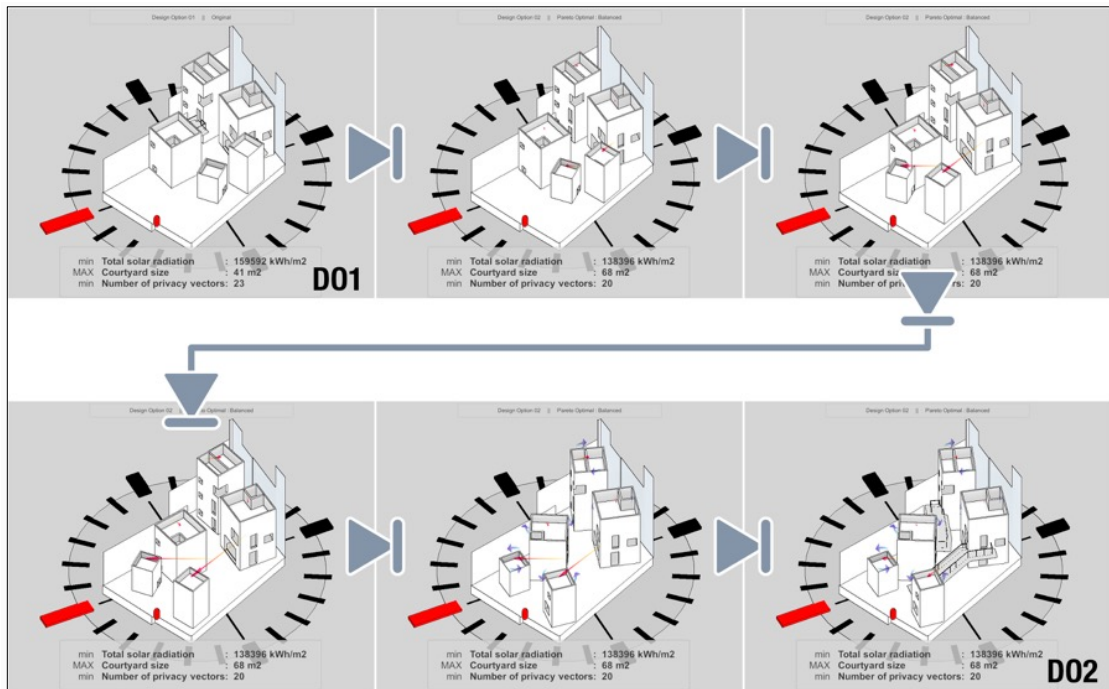


Figure 5.36. Key frame stills that demonstrate the design option morphology feature.

Navigation evaluation mode

When the user selects a design option for further interrogation and qualitative evaluation, he/she may switch from the *dashboard evaluation mode* to the *navigation evaluation mode*. The *navigation evaluation mode* relies on *first-person point of view* to qualitatively evaluate the design option (Figure 5.29). A first-person point of view is one where the user sees through the eyes of the virtual character or camera. For the *navigation evaluation mode*, the user may choose between three visualization methods: a conceptual, a phenomenological, or an analytical visualization method.

Conceptual visualization method

Similar to the *massing axonometric representation* in *dashboard evaluation mode*, the *conceptual visualization method* excludes all details to allow design reviewers to construct their interpretation of the space (Figure 5.37). In this visualization method, the user is assisted by: two persistent floating support viewports, an axonometric massing and mini-map viewports; and a pop-up *parameter viewer* support viewport.

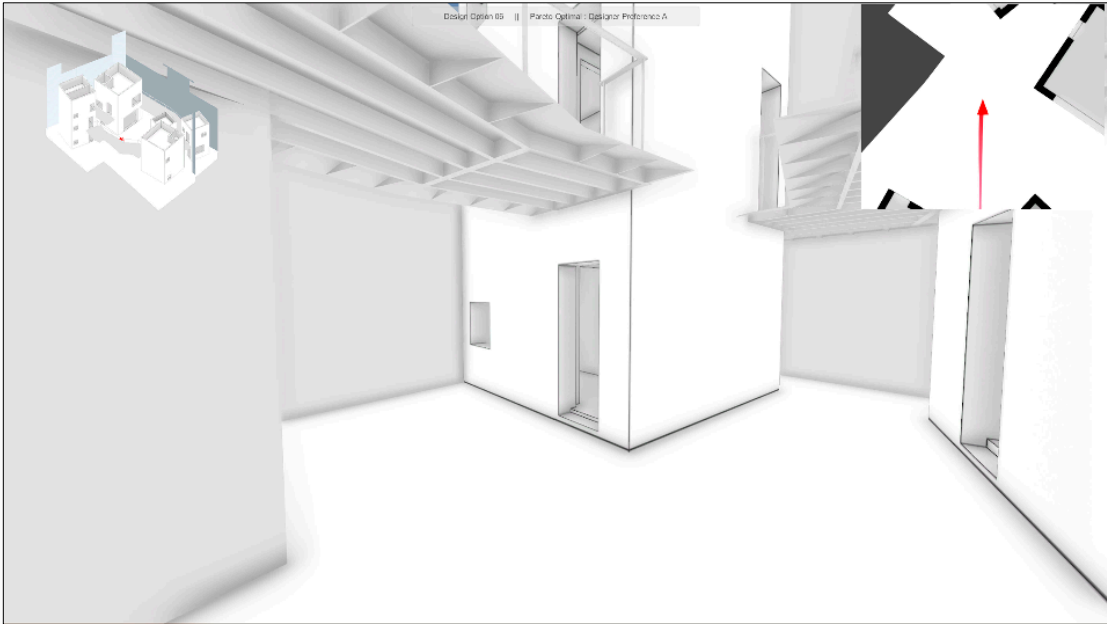


Figure 5.37. *Conceptual visualization method in the navigation evaluation mode.*

The axonometric massing viewport is a miniaturized instance of the massing axonometric model in the *design option description* section of the *dashboard evaluation mode*. Therefore, it inherits all features of the massing model in the *dashboard evaluation mode*. For example, the ability to rotate the camera, the highlighting of user occupied spaces, the animation, the assisting vectors...etc. Thus, if the user toggles between the *navigation evaluation mode* and the *navigation evaluation mode*, both axonometric massing viewports remain consistent. The addition of this viewport assists the user in gaining insight into the general massing of the design option, as well as the user's spatial relationship to the overall model while conducting the interactive walk-through.

Mini-map is a term borrowed from the gaming industry which references the small floating viewport usually placed in the corner of the screen. The mini-map is a dynamic top view of the user in the space used for orientation assistance. The camera that renders this viewport inherits its transformation—translation and rotation—from the user's movement. For example, if the user moves horizontally in the space or vertically

between different levels, the mini-map will update to reflect the user's position (Figure 5.38). For the prototype, an arrow expresses the direction towards which the user is facing. Because the mini-map viewport renders the plan from the user's point of view, the user arrow indicator will always point upwards.

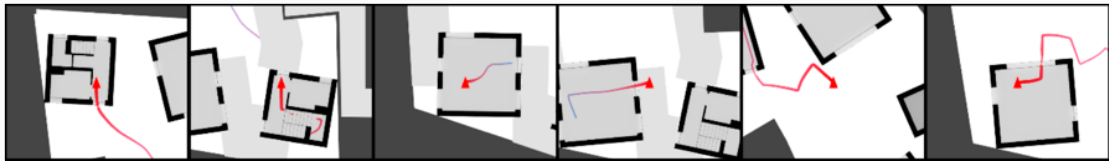


Figure 5.38. Snapshots of the mini-map while a user is in the *navigation evaluation mode*.

The parameter viewer popup viewport may be activated by right-clicking on a particular model element, e.g., wall, window, or floor (Figure 5.39). When the user clicks on an element, a scrollable popup viewport displays the available BIM parameters of the element. All navigational controls are deactivated when the *parameter viewer* is activated. Disabling navigations controls allow the user to scroll and inspect the parameters of the selected element without changing the point of view of the main viewport.

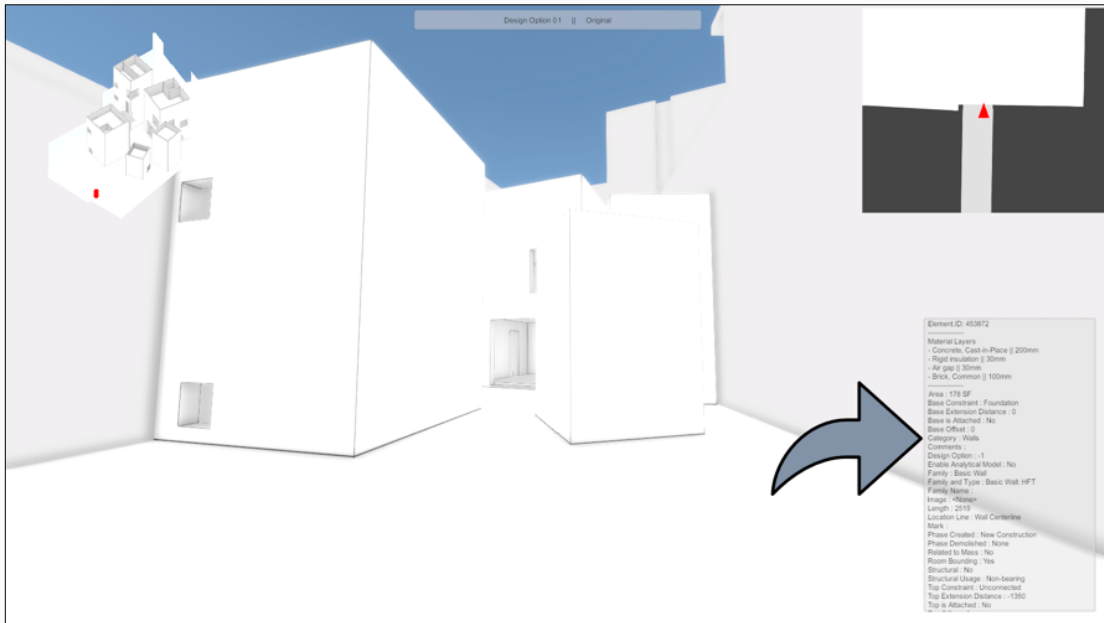


Figure 5.39. Parameter viewer pop-up window.

Furthermore, the user can toggle the results of sensor grid analysis that correspond to the daylight availability and comfort metrics reported in the dashboard. Either UDI or *estimated annual glare potential* and their associated scales may be displayed in the conceptual visualization (Figure 5.40). Therefore, accurate inspection of these analyses for each space and the ten optimized design options is possible while using the *conceptual visualization method* in the *navigation evaluation mode*.

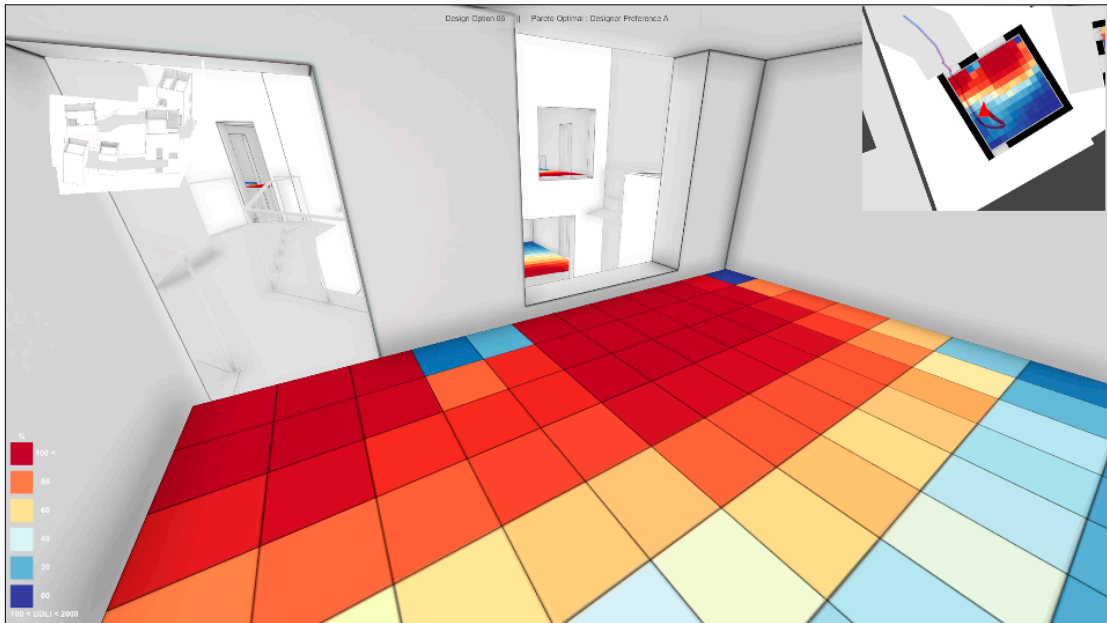


Figure 5.40. UDI simulation results displayed in the *navigation evaluation mode* while using the *conceptual visualization method*.

Phenomenological visualization method

The phenomenological visualization method is a photorealistic rendering mode that uses Unity’s real-time GI to render all design options (Figure 5.41). In this visualization method, the user may comprehensively experience the designer’s intent and the expected outcome of design options. In this visualization method, the highest level of detail for geometries and textures is used. Environmental attributes such as vegetation, direct and indirect daylight, wind, and sound are included. Furthermore, camera effects such as antialiasing, bloom, tone mapping, color correction, and HDRI eye adaption are also used. Additionally, the user may accelerate or decelerate the speed at which the sun moves throughout the day, thus being able to experience a 24 hour period of daylight quality within few minutes or seconds (Rhodes, 2015). Figure 5.42 is a set of three screen captures that demonstrate the moving of the sun throughout the day. Additionally, the user may reveal or conceal UDI and glare probability analysis grids while using the phenomenological visualization method (Figure 5.43).



Figure 5.41. *Phenomenological visualization method while in the navigation evaluation mode.*



Figure 5.42. Screen captures of midday (top), late afternoon (middle), and night (bottom).

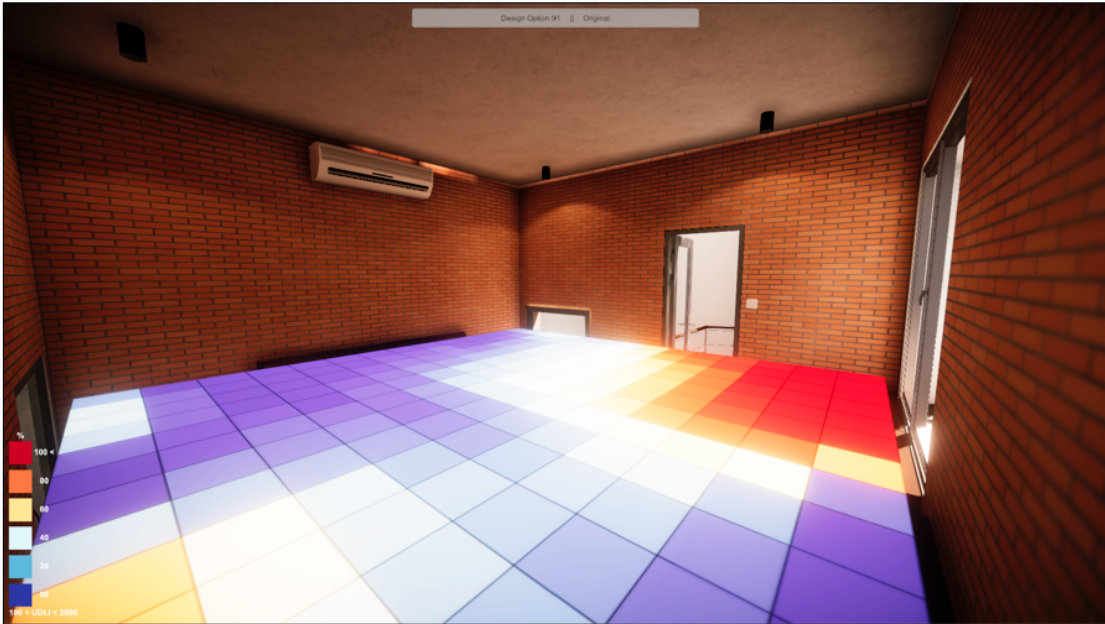


Figure 5.43. Revealing UDI analysis while using the *phenomenological visualization method*.

The phenomenological visualization method is assisted by the support viewports on *display02* and a single pop-up *parameter* viewport. The intention is to remove all possible distractions from this visualization method to maximize immersion. Thus, the phenomenological mode reports a persistent brief description of the design option at the top of the viewport, displays object parameters via a pop-over window and allows the toggle of grid based analysis results.

Analytical visualization method

This visualization method maps a performance metric (total solar radiation amount) directly on the geometric model (Figure 5.44). The method is not meant to dictate or give priority to a single metric over other possible metrics. It is rather an example of what an analytical *navigation evaluation mode* may be. Other simulation-based methods that use per-vertex colored meshes may be used instead of solar radiation. It is expected that the *analytical visualization method* may allow the user to scrutinize analysis results from every possible point of view while maintaining both, spatial coherence and

relativity. In addition to the geometric model of solar radiation analysis, the interface also provides a scale to assist the user in deciphering the depicted colors on the meshes.

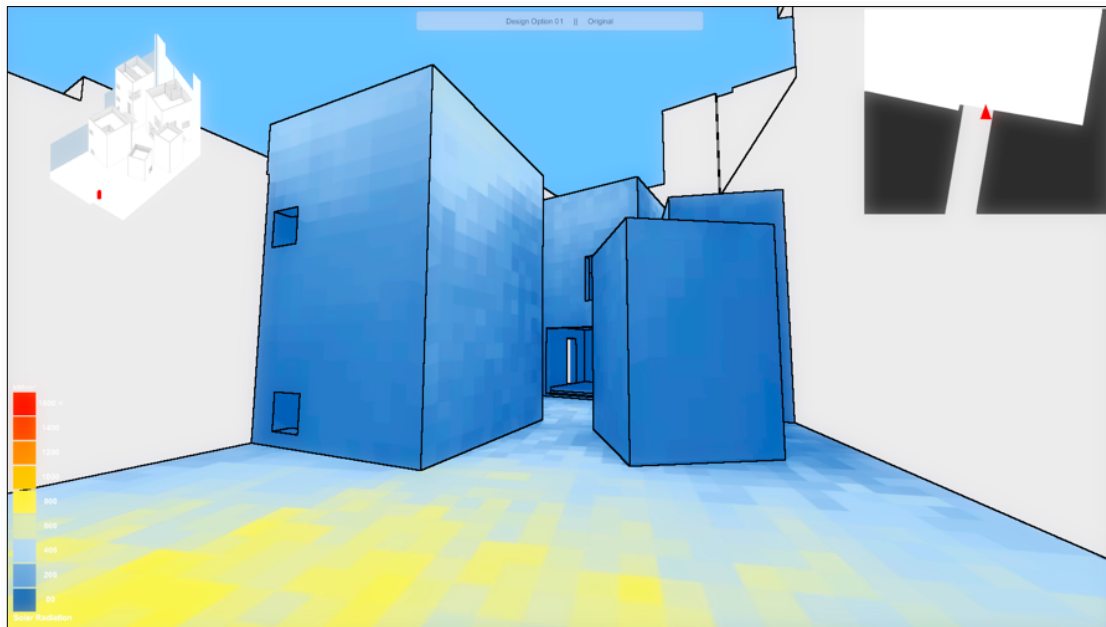


Figure 5.44. Analytical visualization method while using the navigation evaluation mode.

While using this visualization method, the user may toggle the sky-dome model, and cycle amongst different sky-dome models to show direct, diffused, as well as total solar radiation (Figure 5.45). Having access to the sky-dome may quickly provide the user with a broad understanding of where the most intense solar radiations come from, which may, in turn, explain why certain design options perform better than others for this metric.

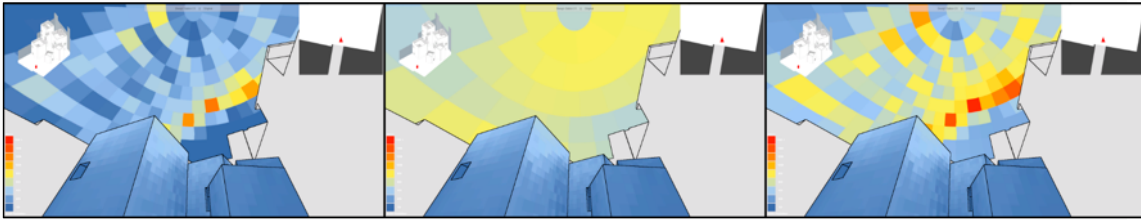


Figure 5.45. Direct, diffused, and total radiation sky-dome models accessible while in using the *analytical visualization method*.

Support display (display02)

Architectural design may not be communicated using a single method or type of representation. To review design projects, it is often necessary to have a multiplicity of representations at different levels of abstraction that may assist viewers in comprehending design solutions (Kalay, 2004). Support viewports in *display02* are ones that may display the multiplicity of representations and information necessary for PDR. The *support display* may contain one or more viewports which may hold different representational media. Figure 5.46 is an example of four out of many possible layouts that users may prefer for a project. As a proof of concept, this prototype utilizes nine support viewports (Figure 5.46).

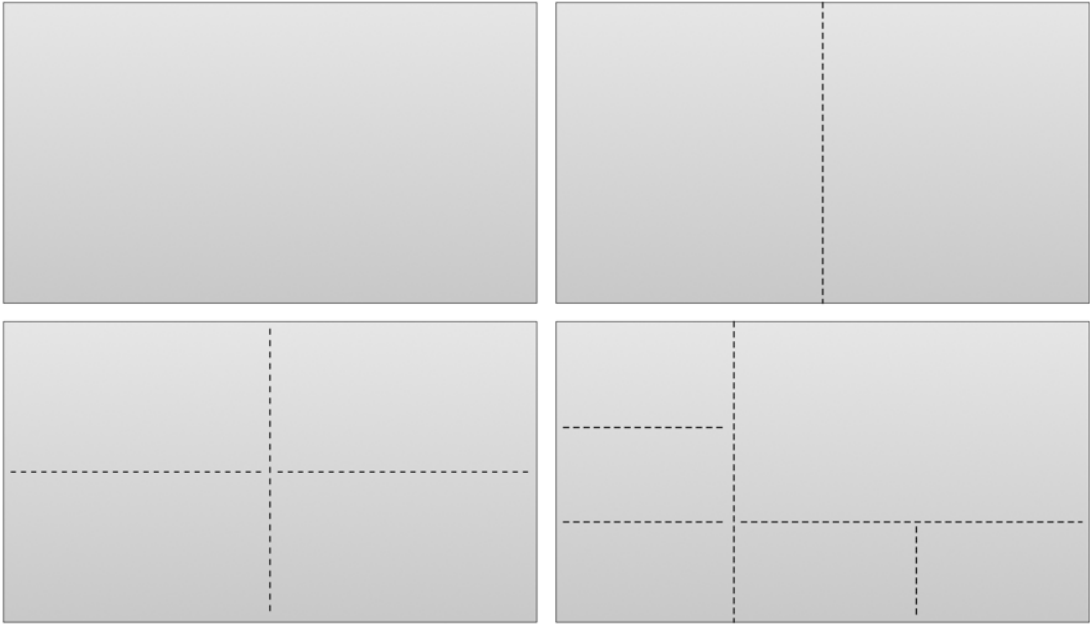


Figure 5.46 Four out of many possible layout scenarios for the support viewports on *display02*.

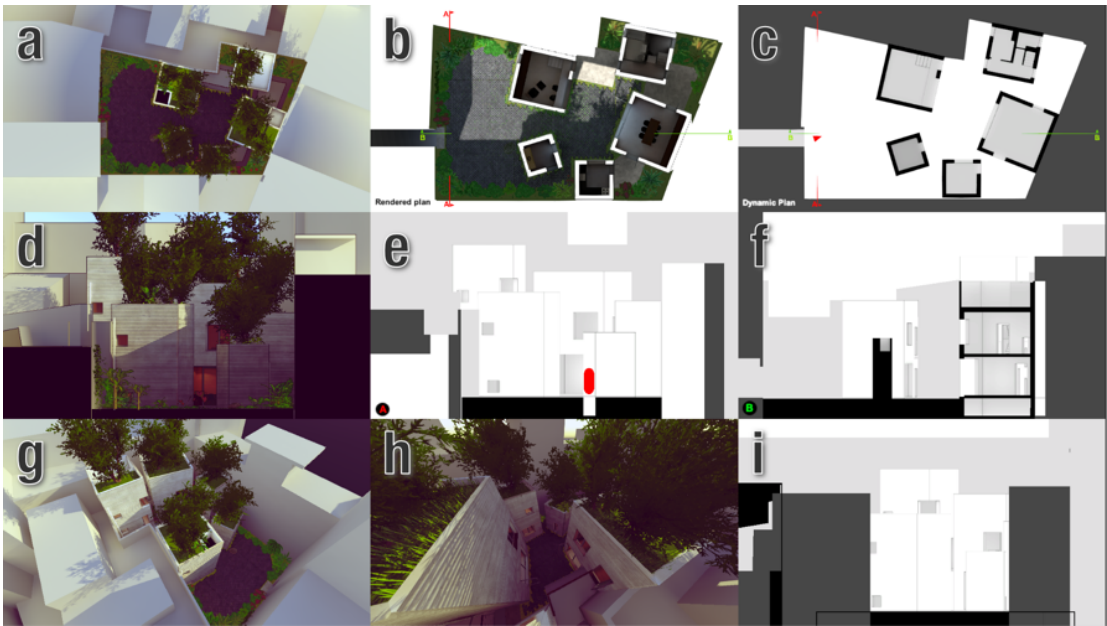


Figure 5.47. Support viewports on *display02*.

These nine support viewports are as follow: (a) a site plan showing limited contextual information; (b) a fully rendered plan which may demonstrate the function of each space; (c) a floor plan that corresponds to the massing model, i.e., excludes texture, furniture, shade and shadow, etc.; (d) a fully rendered elevation which may act as a static image; (e) a dynamic cross section that constantly updates based on the user's spatial location; (f) a dynamic longitudinal section which also constantly updates based on the user's spatial location; (g) a perspective rendering taken from the projects North; (h) a perspective rendering taken from the projects East; (i) an experimental sectional drawing that corresponds to the normal of the main viewports camera. While this viewport may be disorienting at times, it aids in understanding the sectional quality between *boxes* that may never coincide in the other section drawings (e) and (f). Figure 5.48 demonstrates a scenario when *box02* and *box04* may not coincide in sections-A/B.

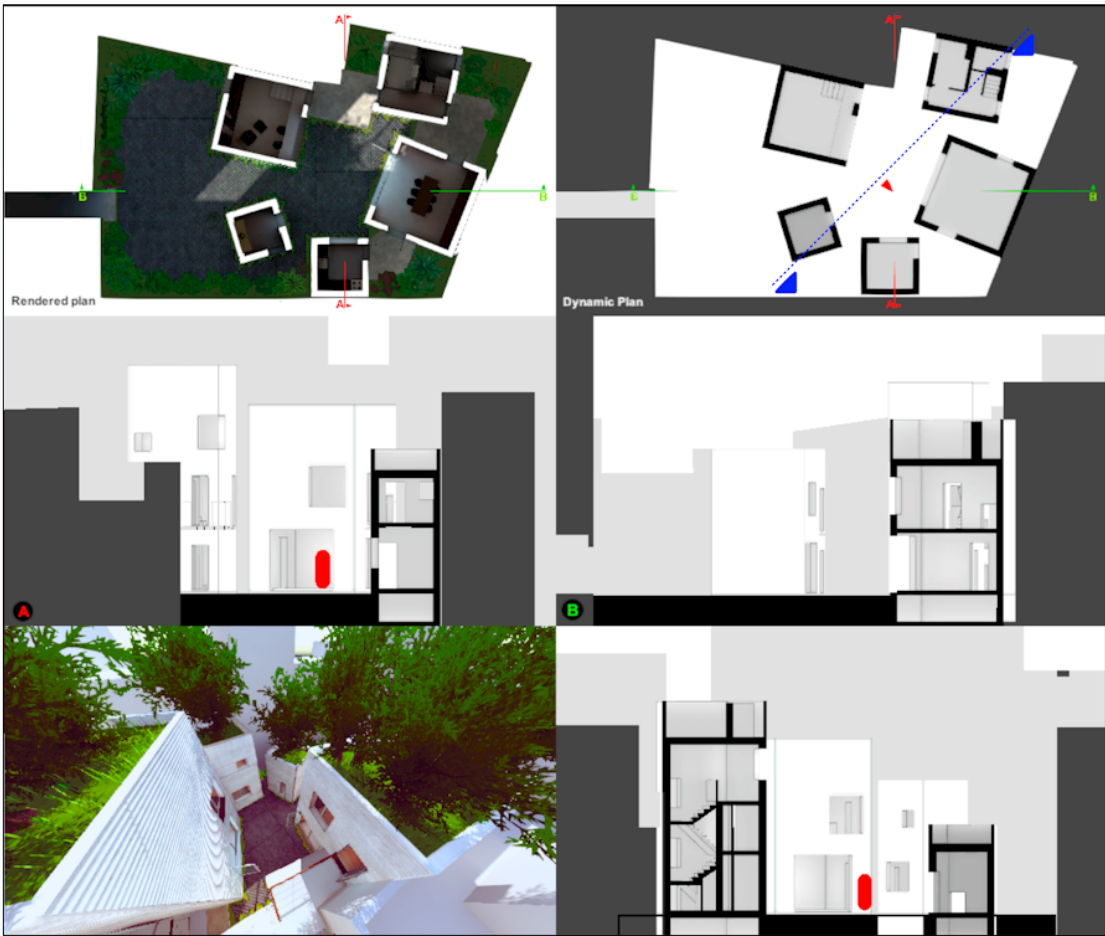


Figure 5.48. Example scenario when *box02* and *box04* may not coincide in sections-A/B. Note the blue section indicator in the upper right dynamic plan is added for clarification, i.e., a post-graphical addition that is not part of the PDR interface.

For the most part, the location of the user is highlighted in the support viewports to assist in obtaining accurate spatial perception in the navigable environment (Fukatsu, Kitamura, Masaki, & Kishino, 1998). For example, viewport (c) in Figure 5.47 displays the dynamic location of the user as well as the section cut symbol for sections-A/B. Additionally, the path a user takes during PDR may also be represented by drawing a line of the user's journey in the design option (Figure 5.49) (Yan, 2006; Yan & HE, 2007).



Figure 5.49. Displaying the user's journey through the space.

5.3. PDR Interface Framework

The framework for the interface is controlled via a *global event method*. An *event* is a *public function* that alerts other *classes* when specific situations occur. It may be explained as a broadcast system that may send specific information to *public methods* that are *subscribed* to an *event*. For example, when a particular situation occurs, e.g., a mouse click, the *event method* is invoked which in turn calls the *method* of *subscribed classes* (“Unity - Events,” n.d.). In the prototype, the *global event method* handles user’s design option selection via the *Function keyboard shortcuts*. When a design option is selected, several methods are triggered simultaneously. The event system manages the display and transformation of geometric and non-geometric data as the user shifts from one design option to another.

For example, if the user presses the *F6* function keyboard shortcut, all viewports will thereafter display geometric and non-geometric data related to *design option 6 (DO6)* until the user selects another design option. The displayed data include all geometric

models whether conceptual, phenomenological, or analytical. If the user is in the *dashboard evaluation mode*, the boxes will be translated then rotated per DO6 data. Accordingly, all data in the *dashboard evaluation mode* will display simulation results associated with DO6, and so on. The *dashboard evaluation mode* (Figure 5.50), *navigation evaluation modes* (Figure 5.51), and all support viewports (Figure 5.52) will only display geometric and non-geometric data associated DO6 until the user shifts to another design option.

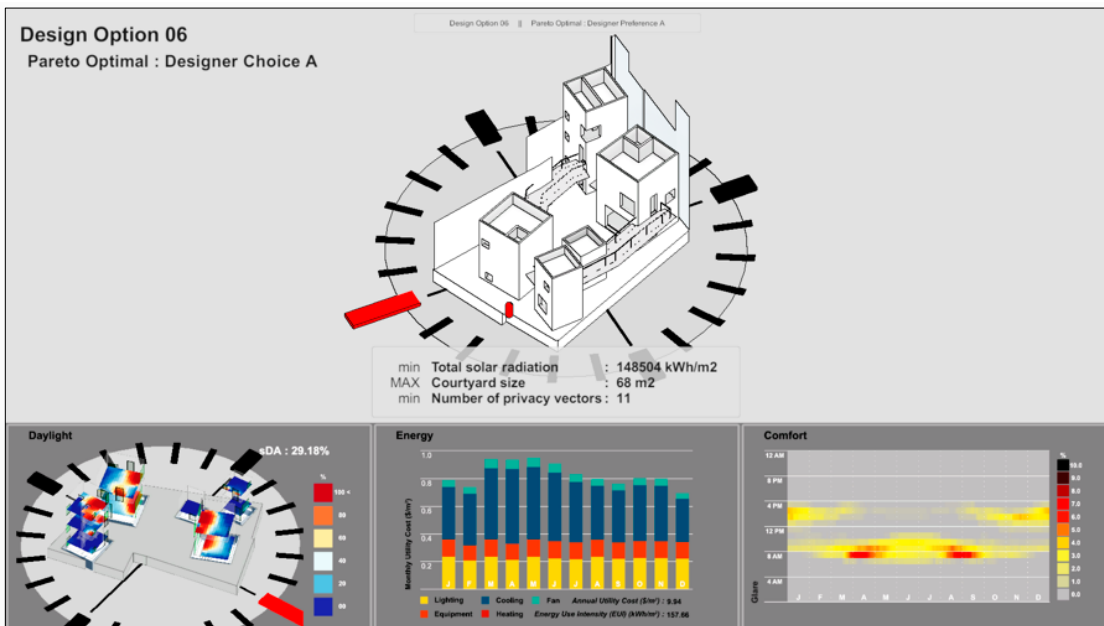


Figure 5.50. *Dashboard evaluation mode* on *Display01* showing *DO6* and associated performances.



Figure 5.51. Navigation evaluation mode on *Display01* showing *DO6*.

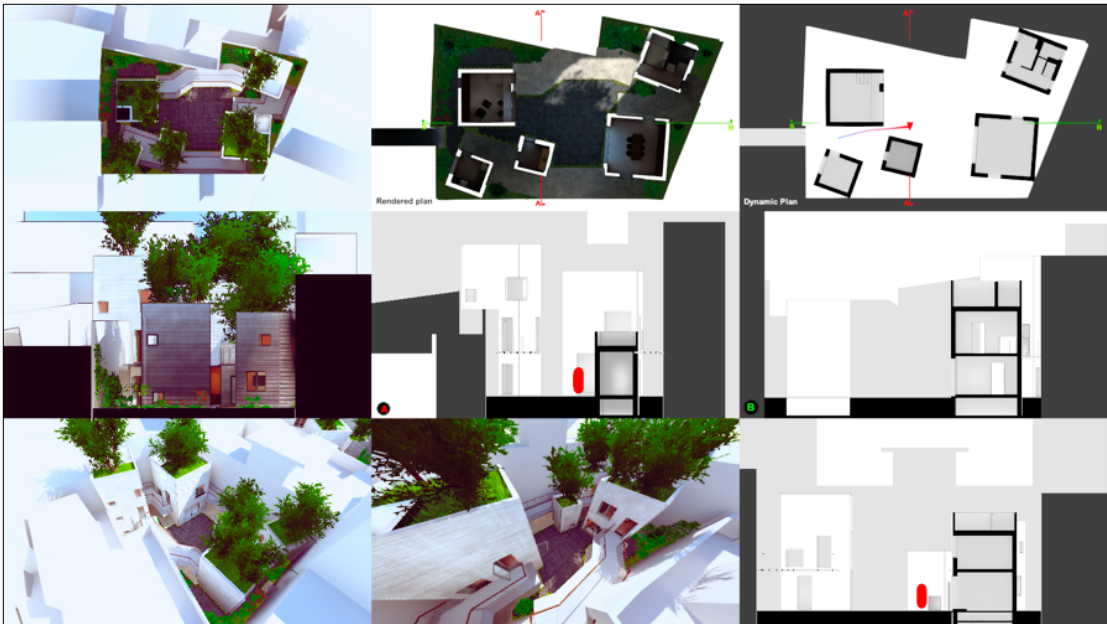


Figure 5.52. Support viewpoints on *display02* showing *DO6*.

5.4. Layering Information

Visual access to the different *evaluation modes* and *visualization methods* is controlled via camera *culling mask* or via custom scripts and toggle keyboard shortcuts. The culling mask property allows the camera to render objects if they are grouped under specific layers selectively. Alternatively, using custom scripts also grants control over individual objects' visibility via keyboard shortcuts. As such, it is possible to have all models and data necessary for the *conceptual visualization* and the *analytical visualization modes* occupy the same virtual space, one on top of another. However, only specific objects related to the evaluation mode or the visualization method are displayed at a time.

Every viewport in the interface prototype is a Unity *camera item*. Each camera has a screen location and size properties that control where it may be drawn on the screen and how much of the screen it may cover. The cameras' location and size properties are used to organize all support viewports in *Display01* and *Display02*.

Each camera also contains a *depth* property. The *depth* value of a camera controls the drawing order when using multiple and layered viewports. For example, the *mini-map floating viewport* is drawn on top of the main viewport because the former has a larger depth value than the latter. This depth property also allows for the separation of geometric models and UI elements where the latter is rendered via a separate camera with a higher depth value. Additionally, the way in which the prototype handles the different visualization methods is also controlled by camera's depth value. A discrete camera is used for each *evaluation mode* and *visualization method*. These cameras are layered one on top of the other. As the user shifts from one *evaluation mode* or *visualization method* to another via keyboard shortcuts, a custom script manipulates the *depth* value to control which camera is rendered on the screen.

A custom script is attached to Architectural elements considered for parameter query. When the user selects the element, the script retrieves the element's data from the parameter file and displays the information using a floating window in the main viewport. This functionality is possible because each element in the FBX file retains the

Revit *objectID* as the element's name suffix (Pauwels, De Meyer, Jan Van Campenhout, 2010).

5.5. Real-time GI for The Phenomenological Visualization Method

The *phenomenological visualization method* relies on realistic, fully textured, and highly detailed models that may closely show the designer's intent. The method uses Unity's real-time GI rendering method to simulate direct and indirect lighting. Only objects that are made *static* in Unity may be rendered using GI. However, objects that are *static* may not be animated, and their rendering properties may not be changed during the design review, i.e., *static* objects may not be hidden/unhidden during gameplay. Therefore, it is necessary to have a complete *static* model of each design option to be able to use real-time GI rendering for the *phenomenological visualization method*. Unlike the *conceptual* and *analytical visualization methods*, where all models occupy the same space in the virtual world, these *static design option models* may not overlap and therefore must be distributed in the virtual space (Figure 5.53).

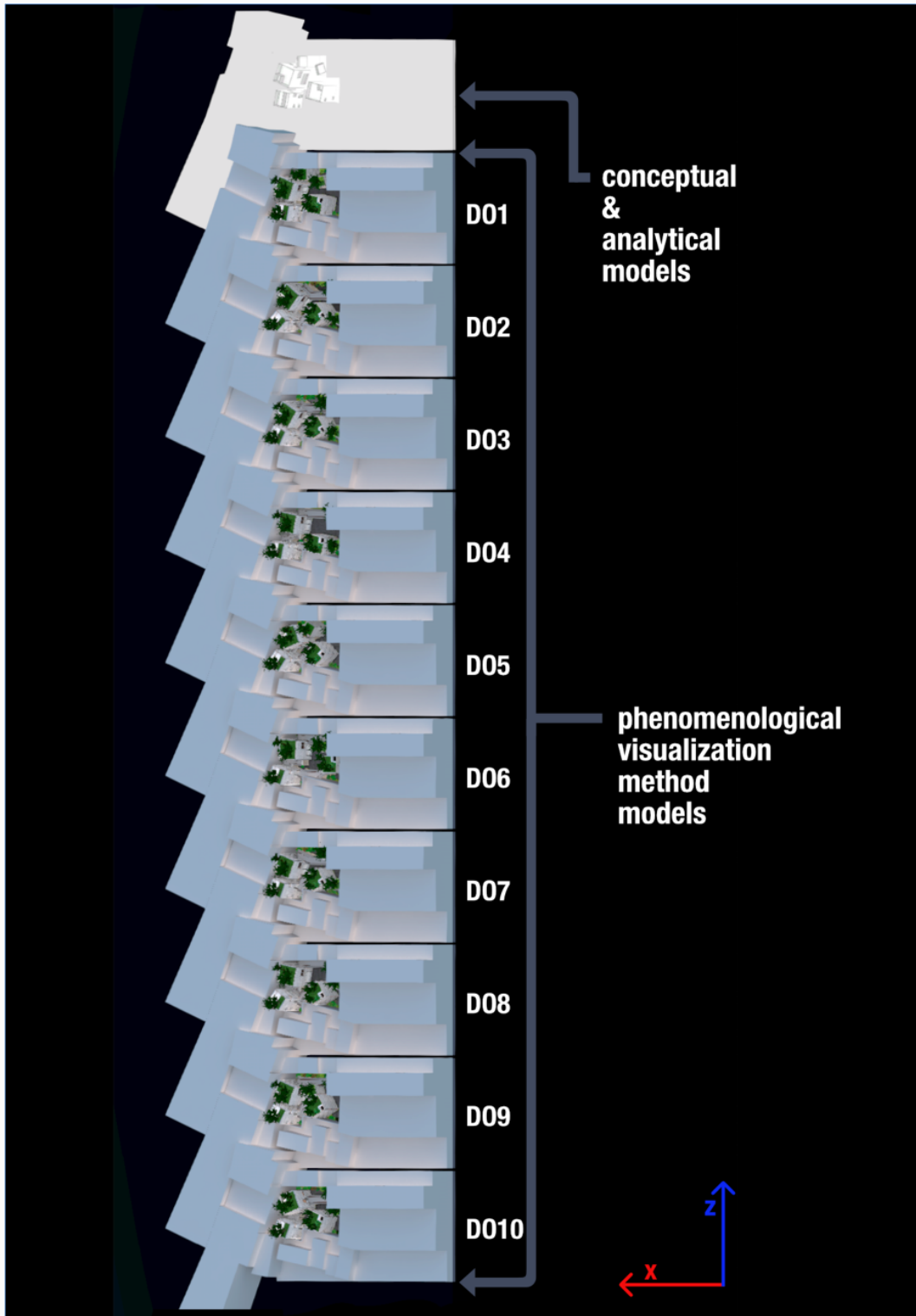


Figure 5.53. Distribution of the design options' models in the VE for the *phenomenological visualization method*. Note that the conceptual and analytical models occupy the same space in the VE.

A custom script manages the ability to alternate the *phenomenological visualization camera* amongst the ten optimized design options. The script inherits then offsets the values of *conceptual visualization camera* transformation matrix. This dependency between the two cameras could allow the user to have a simultaneous rendering of multiple visualization methods. For example, the main viewport may be used for the *phenomenological visualization method* while a support viewport may be used for the *conceptual* or *analytical visualization method*.

5.6. Summary

This chapter is made of two parts. The first part is the processing of geometric and non-geometric data generated from modeling and simulation software to be used in the game engine. The processing of data relies on a DCC software that facilitates geometric optimization and texture baking. A detailed description of the process is provided where *model hierarchy*, *mesh density*, *texture mapping*, *remeshing*, *UV mapping*, *texture baking*, *simulation baking*, and *BIM parameters* are discussed.

The second part of this chapter explains the outcome for PDR. PDR relies on a two-display scenario to review a design project. *Display01* is the main viewport, and *Display02* contains a set of nine support viewports. The support viewports on *Display02* may contain different representation methods that may or may not be dynamic. *Display01* of PDR may toggle between two evaluation modes: *dashboard evaluation mode* and *navigation evaluation mode*. The *dashboard evaluation mode* provides an overview of the selected design option by representing the geometric model of the design option and by reporting multiple performances associated with the design option. The *navigation evaluation mode* provides a first-person point of view of the model. Furthermore, the *navigation evaluation mode* gives access to three visualization methods: *conceptual*, *phenomenological*, and *analytical visualization methods*.

6. FOCUS GROUP EXPERIMENTS, RESULTS, AND DISCUSSION

For validation purposes, experiments by the author were conducted by demonstrating PDR and included functionalities. From the alternatives of worked examples, demonstrations, and trials, demonstration before a focus group provides the optimal combination of data and ease of implementation (Clayton, Kunz, Fischer, 1998). Focus group sessions were conducted with faculty members, graduate and undergraduate students for qualitative evaluation of PDR and further discussions. Focus groups were conducted to evaluate the *perceived usefulness* and *theory confirmation* of PDR.

6.1. Focus Group Experiment

Focus groups are guided semi-structured groups holding discussions on a selected topic, e.g., market research, political analysis, and evaluation research (Dawson, 2002; Ruane, 2005). According to Edmunds (2000), focus groups are an effective to help determine strengths and weaknesses of a product (Edmunds, 2000). One may coordinate, conduct, and analyze focus groups within a relatively short time frame. Additionally, clarifications of participants' comments are easy to obtain during a focus group session (Edmunds, 2000). I conducted focus group session with faculty members, graduate and undergraduate students to validate the PDR interface through *theory confirmation* and evaluate its *perceived usefulness*.

Focus group discussions were conducted where all participants are associated with Texas A&M College of Architecture. Approval to conduct the focus group sessions was granted by the Institutional Review Board (IRB) at Texas A&M University, study number: IRB2016-0217D.

Recruiting participants for focus group sessions proved to be a challenge. Faculty members were recruited via email. First, the research advisor sent an email to faculty members which included a very brief introduction to the research, and a screen capture of the PDR *navigation evaluation mode* (Figure 6.1). The author followed with an IRB approved email transcript that contains a link to an online *calendar*, research abstract,

IRB approved consent form, and a screen capture of the PDR *dashboard evaluation mode* (Figure 6.2). Faculty members interested in participating in the focus group sessions were asked to select preferred time-slots using the online calendar. Faculty members were also encouraged to forward the email to their design studio students. Out of a total of the 29 invited faculty members, 11 agreed to participate.



Figure 6.1 Screen capture of the PDR interface *navigation evaluation mode*.

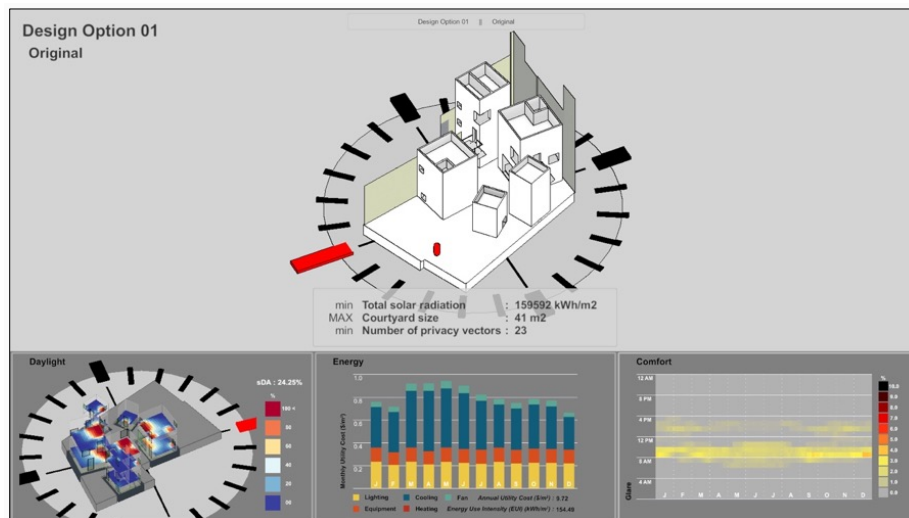


Figure 6.2 Screen capture of the PDR interface *dashboard evaluation mode*.

Graduate students' recruitment was facilitated by email. The author sent an IRB approved email transcript that contains a link to an online *calendar*, research abstract, IRB approved consent form, and two screen captures (Figure 6.1 and Figure 6.2): one of the PDR *dashboard evaluation mode* and one of the *navigation evaluation mode*. Graduate students interested in participating in the focus group sessions were asked to select preferred time-slots using the online calendar. Graduate students were encouraged to invite their fellow graduate students at the department of architecture. Out of 19 invited graduate students, five agreed to participate.

Undergraduate students were recruited verbally after taking permission from the studio instructor. The author introduced the research using the IRB approved verbal recruitment transcript to recruit students from the T4T lab. The T4T lab is a vertical studio that combines senior and sophomore students in a collaborative design environment that embrace the use of digital technology. After introducing the research, students were asked for their preferred time-slot to conduct the focus group session. Students took the initiative to invite their fellow students from other design studios to the focus group session.

In total, four focus groups were conducted. *Group I* and *Group II* were held with faculty members. *Group III* was conducted with graduate students. *Group IV* was conducted with undergraduate students. For *Group I*, six faculty members signed up to participate in the focus group. However, only four faculty members participated throughout the session, and a fifth faculty member joined the discussion towards the end of the session. One faculty member that signed up for the session did not show up to focus Group I. For *Group II*, six faculty members participated in focus group session. A total of five graduate students, three Masters of Architecture students and two PhD students, participated in *Group III*. Finally, seventeen undergraduate students participated in *Group IV*. *Groups I, II, and III* lasted approximately one and a half hours, while *Group IV* lasted nearly two hours.

The author took the role of the moderator in all sessions. All focus group sessions were conducted during the 2017 fall semester at Texas A&M University. The session for

Group I was conducted on the 30th of March 2017. The session for *Group II* was conducted on the 18th of April 2017. The session for *Group III* was conducted on the 20th of April 2017. Finally, the session for *Group IV* was conducted on the 28th of April 2017.

Focus group sessions were conducted at the conference room of the Texas A&M University Embodied Interaction Laboratory (TEILab). The room was equipped with two 65-inch 4k capable displays that were used to present the research problem and to demonstrate PDR. Sound was enabled on the 4K displays to demonstrate sound effects included in PDR.

All of the focus group sessions were video-recorded using two cameras. The first camera (*camera01*) was positioned to capture participants reaction as they observe the PDR, such as none verbal approval body language including nodding in agreement or shaking the head in disagreement. The second camera (*camera02*) was positioned to capture what the participants were observing, which later helped identify what the participants were referring to when discussing what's presented on the screen. Figure 6.3 shows the layout of the session and the placement of the 4K displays and recording cameras.

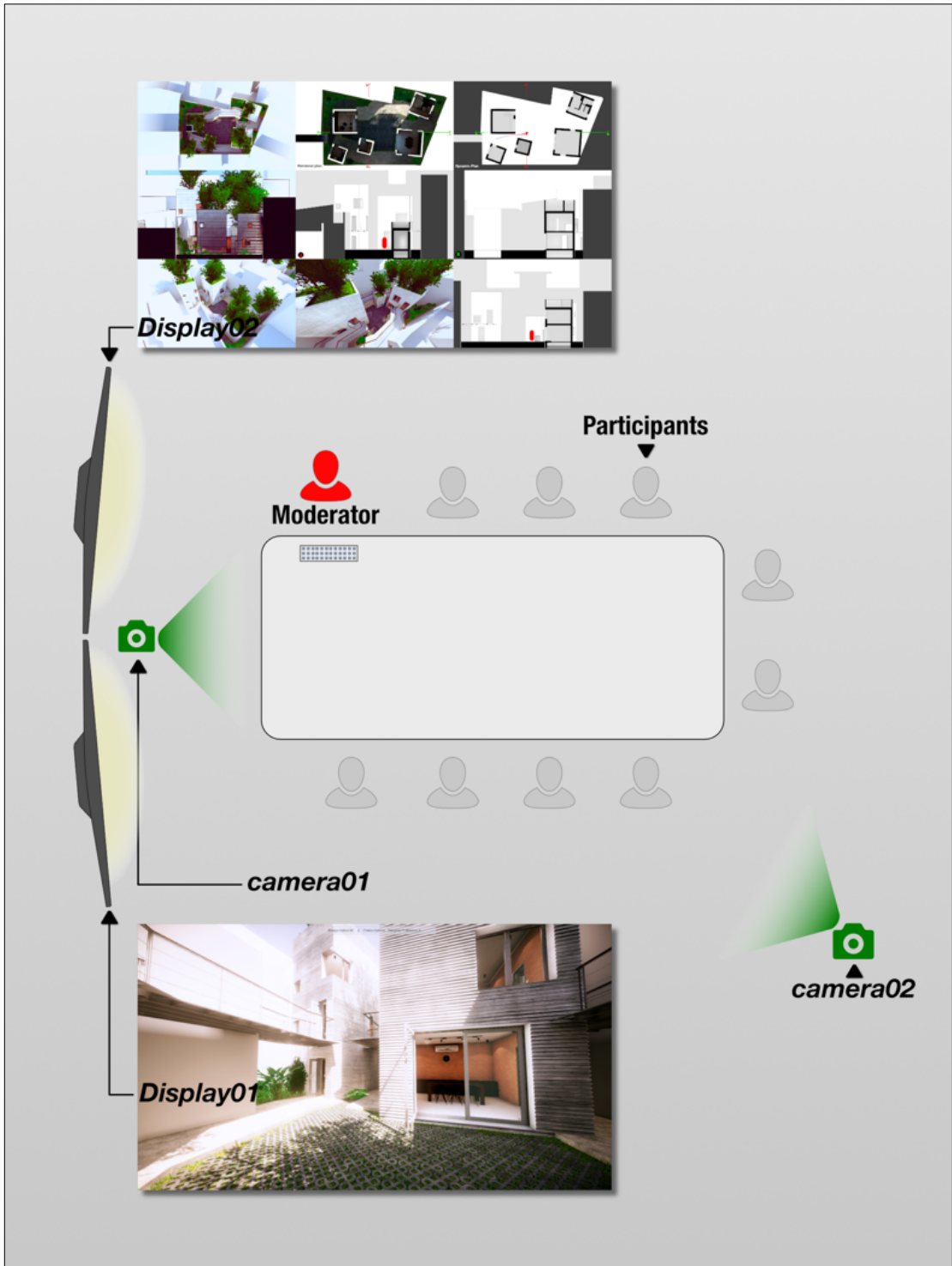


Figure 6.3. Focus groups typical settings.

The moderator (the author) introduced himself before the official beginning of each focus group session. The participants were asked to sign required IRB consent forms before presenting the research and demonstrated the PDR. The moderator presented the research problems, briefly explained the HFT test case project, the parametric framework applied to the HFT to generate design options, and the building performance optimization process. The moderator then proceeded to demonstrate the functionality of the interface by using the completed PDR prototype. The outline of the completed PDR description in Chapter 5 was used as a guideline to explain the interface in the focus group sessions sequentially. For example, the moderator started a live demonstration and interface explanation of the *dashboard evaluation mode* including all textual, graphical, and animated information, then proceeded to explain the *navigation evaluation mode* and the three *visualization methods*.

After the moderator concluded the presentation, participants were asked to reflect on a series of questions regarding the presented prototype and comment verbally. The moderator expressed that the aim of the focus group was to gather data about the *perceived usefulness*, not the *perceived ease of use*, of the PDR. Participants' responses occasionally influenced the direction of the focus group discussions and follow-up questions. Participants were not granted a hands-on experience with PDR. However, in multiple instances, participants asked the moderator to move around the building in the *navigation evaluation mode* or alternate between different *visualization methods* to help clarify their questions and observations. Questions raised by participants were either answered by the moderator or became the topic for further discussions amongst the participants. The following link is of a video screen capture of PDR which may serve as a sample of what was demonstrated at the beginning of each focus group session:

<https://vimeo.com/239478257>

6.2. Results and Discussion

By using the video-recordings, the author transcribed the four focus group sessions. Body language and explanation of participants' intents, when available, were also transcribed by inclosing those observations in parenthesis following each sentence.

Analysis of the focus group discussions involved categorizing and organizing responses into several constructs. The categories were generated from the research problems, proposed functionality in the interface, or emerged from the focus group discussions. For example, the *ease of use* of the PDR method is outside of the scope of this research. However, an overwhelming set of responses in the focus group sessions revealed that ease of use is an essential quality for an effective implementation. Therefore, although not an objective of the focus group session, responses that suggest that the ease of use is an important issue were included in the discussion.

For this study, the main construct is *the perceived usefulness of PDR*. However, sub-constructs that qualify the usefulness of PDR were considered before conducting focus group sessions. Other constructs emerged from analysis of focus group discussions. The constructs that were considered and ones that have emerged from the focus group discussions are as follows:

1. The perceived usefulness of PDR, in general.
2. Participants' rating of PDR.
3. Participants' willingness to use PDR.
4. The perceived usefulness of multiple real-time viewports and automatically generated drawings.
5. The perceived usefulness of integrating performance-based analysis.
6. The perceived usefulness of the inclusion of multiple design options.
7. The perceived usefulness of animated design option morphology.
8. The perceived usefulness of real-time section drawings.
9. The perceived usefulness of utilizing different visualization methods.
10. The problem of perceived information overload.
11. The potential of PDR as a replacement for paper-based design reviews.
12. The potential of PDR as a design tool.
13. The potential of PDR outside of academic settings.
14. The importance of perceived ease of use for potential users.
15. Suggested enhancement to PDR.

The following discussion provides a detailed description and analysis of each construct. Note that some responses may address more than one construct. Therefore, the repetition of responses is necessary to communicate focus group analysis and results comprehensively. Additionally, to clarify some points, certain dialogs amongst the participants are provided as is. In those cases, for example, faculty members are identified by the prefix (FM) and a character letter from A-D for *Group I* and F-K in *Group II*. In the case of graduate students who participated in Group III, the prefix (GS) followed by a character letter is provided. For undergraduate students in Group IV, the prefix (Sr.) and (So.) are assigned to seniors and sophomores respectively followed by a character letter.

6.2.1 *The perceived usefulness of PDR, in general.*

Focus group discussion data reveal that in general the ideas demonstrated using PDR are *perceived useful* for both academic and professional practice settings. All faculty members who partake in the focus group expressed that they would encourage the use of the tool, or use it themselves. All students who participated in focus group discussions stated that they would use the tool if available. Some participants questioned its applicability to specific design studio agendas, while others were concerned with *ease of use*. Several enhancement suggestions were made by focus group participants. These enhancement suggestions are reported below as well as in the *future work* section of this dissertation. Analysis of focus group discussion responses, associated with the *perceived usefulness* of PDR is as follows:

Group I

FM-C: So, your research question is how is that applied to design review. Specifically, for design review. I think that it's a fantastic tool if I have all those clients, real project, they have that kind of tool during the design review, I think that is great.

FM-A: I am also interested in this tool, for future work, as a way to teach consequences of design decision... this, has the potential to, in the later stages of the program, to teach in real-time, hyper-real-time, the consequences of certain design decisions. So, it would be really interesting (another faculty member nodding in agreement).

FM-B: Also, the kind of problem, the internal problems of the culture of architecture in schools that: "well, this project can't be made, so this is not architecture"(another faculty member nodding in agreement and smiling). You know, the one I hear all the time. So, I put this (the design that they say cannot be made) into this (the interface) and say: "Yeah well, here it is!". You know?

FM-B: Yeah you can walk it, you can occupy it. So, to me it is more than a design tool, it is really used for a lot of assurance, validation, demonstration, etc. (another faculty member nodding in agreement).

FM-D: ...One thing that I like about this is makes visible something that is invisible for some people. That you (pointing at another faculty member) mentioned about you make some decision and it is not visible for clients. So, you show just the product or the end process of something. But in this way, you can share the process, at least the parameters that you choose. And I like the thing you said (referencing another faculty member) that you see the consequence even as a designer, it is nice to see the consequence on the decision that you made, and you see it in this stage. I think I am with you said (referencing an earlier comment made by another faculty member) without rendering has more performance (more useful) for the designer maybe. With the render maybe for the client or people that cannot visualize it in the final stage. I still think it has benefits for the

designer as well, to see and make it visible that what we decide and how it gonna look at the end. It has more than rendering....

***FM-A:** So, being able to pre-visualize in all these representation modes is inexhaustible in its potential. Once this is approved, and it is a proven tool then you got your billion-dollar venture capital and you want to develop it, then you make it as such that I can expand the thickness of my walls, change everything related on the materials that I'm using (pointing on Display02). Introduce all these passive climate responsive features. And everything happens before the ground is broking on the project.*

***FB-B:** Honestly, I think you should also show it in offices. HKS, John Bailey, healthcare. Showing it to that community is quite important. And also, people like Jose Sanchez. Get some input. This is a different thing. This is not a design tool, this is not about doing your project, this is about any project being input here, be it academic or in the practice and looking at different options. It could be a floor plan for healthcare, and you say: "Where do you put all the rooms?" Or just a simple house project that you want to show the client.*

***FM-A:** I think if someone acquires your idea and develop a plug-in for all the design tools will be great. The beauty of it then is that a lot of times our students default to digital tools of representation in a way that undermines their spatial understanding, but I don't think have the risk of that here. This sorta facilitates spatial understanding ... For integrated it is fantastic. The irony is that you developed a tool which is a plug-in for digital design suite that reasserts and even increases the importance of architecture through the process. Cause a lot of time people are afraid that pretty soon you just type what you want and an*

Autodesk product will design the whole thing. But this, is the opposite of that. It is saying: " This is why you have to have the architect."

FM-B: I agree. Anything at this point in time that reasserts the role of the architect and evaluates their job is super good.

FM-B: It is great.

FM-A: Once again, even in the pedagogical sense it reasserts the importance of the architect (another faculty member agreed: Yes totally).

Group II

FM-K: Very useful.

FM-G: Yes, I can see that right now it is a presentation tool but I can see it easily developed into a design tool, exploratory because if I design something and I can assess what is the value of privacy, or what is the value of solar, or the value of windows it becomes also a tool of design decisions. I can plug in one alternative, plug in another alternative and see which alternative I would like to present at the end, and then make a presentation. So, I can see it being not only just as presentation tool....

FM-G: I would adopt it into a design studio.

FM-K: ... What I find really, really, fascinating is you have got this 3D environment, which I am gonna talk about from this generational perspective... If the goal is to get student to understand a two-dimensional abstraction and what it means in a three-dimensional space, now we have a tool we can experiment with. I think that is a very powerful thing. That you can have them construct some

*environment in three dimensions and it generates these two-dimensional representations because that is currently the language we are tied to... I think, this as a tool to help people begin to understand what their drawings are representing, is very, very, powerful. I say this in integrated and studio reviews all the time, because their drawings are c*** (bad)....*

FM-K: I can say from two points, one of them we just talked about. generating spatial understanding and how is that communicated in three-dimensions and two-dimensions. Then linking that to the performance data is really powerful so that someone learning these things can begin to understand what moves make those changes....

FM-F: ... From the developer's point of view, I am not looking for a tool where I become a designer. I am looking for a tool where there is multiple of sensitivities which give me an understanding, you've got three criteria that you used here: minimum solar radiation, maximum courtyard size, and minimum privacy vectors. Any design is a tradeoff. Multiple elements, right? So, if I can see what the tradeoff is I can begin to understand what the cost and benefits are of a particular solution. You talked in very loose terms about phenomenology. From the point of view of the consumer, that's all the developer does, he connects the designer to the actual person buying. What they are always looking for is a good fit between what they are looking for from the place, and what's available to them. This is a great tool to give an almost photoreal experience to them... I have been looking for a long time now for a tool that allows me to trigger all five of the senses. To the extent to this tool could marry the visual and the auditory to trigger the other two, taste is very difficult thing to trigger, but the other two are relatively easy to trigger with sophistication. I think you

could do that with this tool and I think it would be very powerful... We have this incredible reservoir of tacit knowledge that something like this (the interface) can drag it forward. That doesn't make us architects. We are not, right. You are trained in design and aesthetics that I am not. But every person in the world can tell you whether they like that place or they don't like that place. Or whether they feel ambivalent towards that place. And that is the decision that is important to us as a developer....

***FM-H:** To me the most interesting feature of this one, or the most useful feature, is the correlation that you show between scientific data and the space (another faculty member nodding in agreement). I can easily see how to teach students based on that and do minor design variations and see the effects. Because I think it is hard to teach them if you have only one existing example and do analysis. Because they don't see how moving windows around would affect the function or the performance.*

***FM-J:** Yes, I think we are all honing on exactly the same thing over here and that is the real standout value is that you are looking at things three-dimensionally, that you can move and change around at will, and you are seeing some representation of data from a more objective analysis of the variables....*

***FM-K:** ... I think it is pretty useful.*

Group III

***GS-C:** I think this software is quite useful because after you finish your model, you get all the perspective views, all the renderings, floor plan, sections.*

GS-E: I think it is pretty evident over here. This is kinda standard review pin up (Display02). You get big posters, plan, plan, elevation, couple of perspectives. Here you are moving that's the main one, and you are moving where you want to be moving rather than a scripted fly through celebrating your design. Whereas here you can nose around. I think if someone hands me a model and I can look at it where I want to look at it.

GS-F: I totally agree. So, you show us this video here and plus you overlap this graphically effects of sunlight. It is powerful thing of your work. Especially, there is a similar program like Lumion, just to walk through. But you have very informational data to people. It is a very powerful thing I think.

Group IV

So. A: It is super cool.

Sr. B: I think it is really great cause it addresses the change (parametric change) ... It better addresses the complexity of the digital.

Sr. C: I love how this is a game but it could be a reality because it is a living building. So, what I think is really awesome is you think like you are playing a game but you have so many options and visually it is easier to understand. I think moving things are hard to understand something sometimes, but like with these nine visual representation (support viewports on Display02), Oh ok I can clearly see how they interact. When it is a physical model you don't have that capability.

So. D: I really like the fact that when you change through the different design iterations you can see on all of the different drawings

how they transition (a sophomore and a senior student nodding in agreement). And can see it when you're standing as if you are there and they are moving (in the main viewport).

***So. E:** Similar to what **So. D** is saying I think all the times when you are designing or looking at design options you get stuck in one form of drawing. You get stuck in designing the plan and forget what the section looks like, so it is really cool to be in position where when you change something in plan immediately you see how it affects the section (citing the real-time update of the support viewports).*

***So. F:** I can see this as a plug-in for design software and be able to walk through the building and like ... was saying have the ability to see it in real-time when you want to change some stuff.*

***Sr. J:** I think it is a cool design tool, but also as a method of representation for people seeing the building. Just cause we tend to work in plan and section and we try to find the best view and this gives you the ability to see every single section and every single view which, and it is not flat but you can also rotate and I think that's really, really, cool too.*

***Sr. H:** I think it is really great for the practice and the client. Because maybe as architects we can understand things in plan and section and begin to visualize the space (mentally). But I know that other people are not trained like that. So, I think these kinds of possibilities for them would be really helpful. Having quick changes and different possibilities you can cater to what they want would be really crucial in the practice. I don't know whether, I am still deciding whether I think it is the best for students ... But I think for the practice I think it is something that could be really, really, great. Especially*

having something that different views (pointing at Display02) and the 3D model (Display01).

Sr. I: Yeah, I also think for conceptual design and showing to clients and showing people quick options....

Sr. J: I feel like this could be a useful presentation tool that allows the focus to be more on your experiential qualitative things that are hard to get to in reviews (two sophomore students nodding in agreement). Cause the second they see all these things (the support viewports on Display02) you are always in check. It is either gonna have to work or it will be obvious in the section (that it is not working) (two senior students nodding in agreement). You can show just "a section" and hide the work. I feel like it ups the standard for how worked out and the quality of your project cause you know they will be able to see it at any moment and experience it whether it works or not. So then once they see that they can kinda trust you for a little bit while, so they can focus more on the walk-through or the experiential part of it which I think is a really good thing (a senior student nodding in agreement).

Sr. K: I think in terms of relating this to my projects, it was a pavilion that uses different point of views on campus, so I provide one section however they wanted to see multiple sections of how my building interacted. Because we print on 2D surface, you can't really get that kind of view of all these other sections. So, with this, and the viewpoint of the character (referring to the experimental section cut) you can get a representation of an unlimited amount of sections and so using this would be very helpful for me. I also feel like the way that this is kinda laid out it is very hard to kinda lie (a sophomore and a

senior student nodding in agreement) in terms of ... it kinda ups the game....

So. L: Like everyone has been saying, the representation is definitely a good way to fully inform the viewer. Just how in the project you can't really represent the entire project with a couple of images, this is a good way to fully visualize your project.

So. M: The complexity of the drawing and having the multiple options and these sections and these plans, and how they change a long with each other, the experience based thing, presentation wise it kinda takes away from the "what if". Cause when you are looking at the presentation kinda "what if this was something else, what if this was elsewhere?". I think that definitely kind of has the viewer almost invested in the project and seeing what they like best and I think it is super interesting.

So. N: I think as we were saying, it is successful in the experiential immersion, and the ... of the orthographic views for reference....

So. O: I thought it would be a really cool tool to help students visualize and experience the space that he/she is creating, whoever is designing a house or a building or whatever it is. It actually gives you a better connection with the project than just having a 3D model of your project and printing the sections and 2D perspectives and I think it is really helpful.

So. P: I think the interactive aspect to it is really helpful and makes it a lot more interesting for representation. People interacting with it like this might make it easier or open up new possibilities to express designers' ideas or thoughts about the project.

So. Q: I like how the BIM side of it is really present. The workflow itself speeds it up so much. As it is I don't see it as a presentation tool, more of a design and production tool producing all these plans and scenes from this one model....

So. N: ... regardless of whether or not this will replace paper, I think it necessarily restructures the way in which we design. We say we design in three dimensions and that's why we build models. But when you incorporate the visual effects, sound, this whole immersion experience, I think it is very e-motive and I think that it places a really big role on how we design. So, I think there will be a change in our mind.

Focus group data, therefore, confirms that ideas demonstrated using PDR, in general, were perceived useful for both academic and professional practice settings.

6.2.2 Participants' rating of PDR

Focus group participants were asked to rate PDR (from 0-10, 10 being the highest possible positive rating). In general, participants have rated PDR highly. The question of rating the prototype was not asked in the first focus group (*Group I*) but was brought up by the moderator in subsequent focus group sessions. Almost all faculty focus group participants were enthusiastic and had highly rated PDR. Analysis of faculty focus group discussion responses associated with rating PDR is as follows:

Group II

FM-K: ... I will give it a 7. I think it is pretty useful... 7 to 8.

FM-I: Who is using it? If it is the students it will go off the scale, above a 10... if I am the user... I would give it a 7.

FM-G: ... If you would ask me for a design student, I will say 10 or 9. As a design tool that produces alternatives I will say 9. Still the

10 is to have more forms of heights and other elements. For an architect in the practice, I will have to say 8...

FM-F: From my selfish perspective, it is gonna be upper end 9....

One faculty member gave the proposed PDR interface a rating of 5 out of 10:

FM-J: My gut feeling is that it is good. Would I use it. NO. I am not a zero. I may not use it for what you think, I may use it for demonstration. I may use it for an entirely different thing. I would give it a 5. If it is demonstration, the total thing I would give it a 5, because I would use it for something that is totally foreign to what generated it.

Graduate and undergraduate students focus group participants have rated PDR highly. One graduate, two sophomores, and one senior student have given PDR a 7 out of 10. Three graduate students, three sophomores, and three senior students gave it a rating of 8 out of 10. Three sophomores and one senior student gave it a rating of 9. One graduate student gave it a 9.5 rating out of 10. Finally, two senior and two sophomore students gave PDR a rating 10 out of 10. Focus group data, therefore, reveal that PDR is highly rated by faculty, graduate, and undergraduate focus group participants, i.e., PDR is *perceived useful*. Table 6.1 and Figure 6.4 provide a summary of student's rating of PDR.

RATING (0 to 10)	GRADUATE	SENIOR	SOPHOMORE	TOTAL
7	1	1	2	4
8	3	3	3	9
9	0	3	1	4
9.5	1	0	0	1
10	0	2	2	4
				22

Table 6.1. Summary of students' rating of PDR.

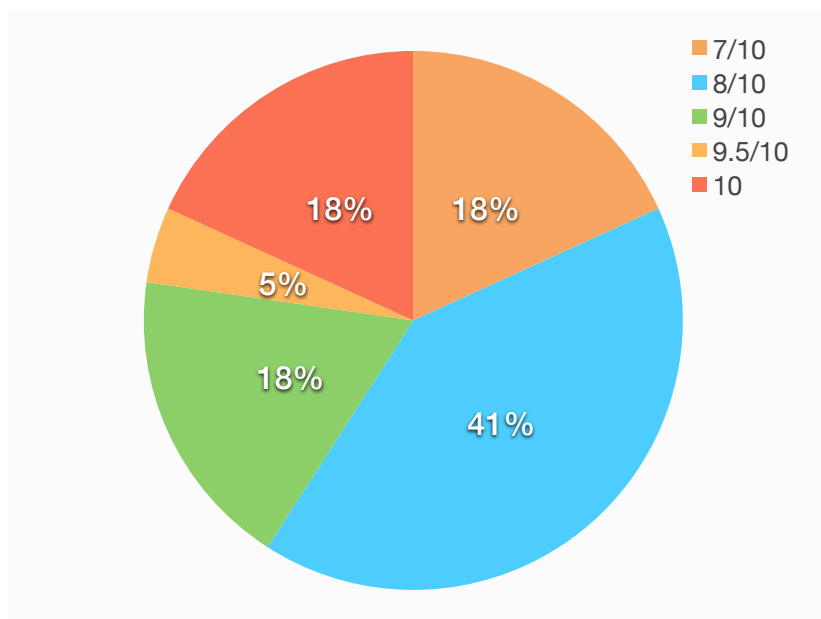


Figure 6.4. Students' rating of PDR.

6.2.3 Participants' willingness to use PDR.

Focus group participants were asked, "if this tool was available, would you use it?" The question was meant to indicate if the participants perceive PDR as useful. This question was brought in *Groups II, III, and IV*. Although the moderator did not ask this question during the session for *Group I*, the answer to the question may be implied by the discussion during *Group I* focus group session. In general, all participants in *Group's*

II, III, and IV have unanimously answered “Yes” they would use PDR. Some participants conditioned their answer with questions of the *ease of use*. Other participants conditioned the answer with the pricing of the tool. Moreover, some participants conditioned their answer with design studio requirements. However, when asked to disregard these conditions assuming for best case scenario and given the demonstrated capabilities, all participants in *Groups II, III, and IV* explicitly stated that they would use the tool. One participant said he/she would prefer to hand draw. Analysis of faculty focus group discussion responses associated with whether they are willing to use PDR is as follows:

Group I (implicit)

FM-C: So, your research question is how is that applied to design review. Specifically, for design review I think that it's a fantastic tool if I have all those clients, real project, they have that kind of tool during the design review, I think that is great.

FM-A: I am also interested in this tool, for future work, as a way to teach consequences of design decision... this, has the potential to, in the later stages of the program, to teach in real-time, hyper-real-time, the consequences of certain design decisions. So, it would be really interesting. (another faculty member nodding in agreement)

FM-B: Also, the kinda of problem, the internal problems of the culture of architecture in schools that: "well, this project can't be made, so this is not architecture". (another faculty member nodding in agreement and smiling). You know, the one I hear all the time. So, I put this (any design that they claim cannot be made) into this (the proposed PDR interface) and say: "Yeah well, here it is!"... you can walk it, you can occupy it. So, to me it is more than a design tool, it is

*really used for a lot of assurance, validation, demonstration, etc.
(another faculty member nodding in agreement).*

***FM-A:** ... So being able to pre-visualize in all these representation modes is inexhaustible in its potential. Once this is approved, and it is a proven tool then you got your billion-dollar venture capital and you want to develop it, then you make it as such that I can expand the thickness of my walls, change everything related on the materials that I'm using (pointing on Display02). Introduce all these passive climate responsive features. And everything happens before the ground is broking on the project.*

***FM-A:** ... I think if someone acquires your idea and develop a plug-in for all the design tools will be great. The beauty of it then is that a lot of times our students default to digital tools of representation in a way that undermines their spatial understanding, but I don't think have the risk of that here. This sorta facilitates spatial understanding. Like ... said, it is not good for first or second year, for upper levels I think it is pretty good. For integrated it is fantastic. The irony is that you developed a tool which is a plug-in for digital design suite that reasserts and even increases the importance of architecture through the process. Cause a lot of time people are afraid that pretty soon you just type what you want and an Autodesk product will design the whole thing. But this, is the opposite of that. It is saying: " This is why you have to have the architect."*

***FM-B:** ... I agree. Anything at this point in time that reasserts the role of the architect and evaluates their job is super good.*

***FM-A:** ... Once again, even in the pedagogical sense it reasserts the importance of the architect (**FM-B:** Yes totally).*

Group II (explicit)

FM-G: I would adopt it into a design studio.

FM-F: Of course (when asked if he/she would use the tool if available), I've not seen anything like this before. And the stuff that ... did was not as detailed, it was not as close to photo real even though we did it in the BIM Cave... there is nothing choppy about this. It has a flow and a navigation, it's quite persuasive.

FM-H: ... Yes, I would (adopt the tool or use it) ...

When the moderator asked the same question again at the end of the session all faculty members explicitly said “Yes,” they would use the tool. Except for one student who preferred to hand draw, all participants in *Group III* and *Group IV* have explicitly stated that they would use the tool if it is available.

Focus group data, therefore, confirm that faculty members, graduate and undergraduate students, would use PDR if the tool is available. Therefore, PDR is *perceived useful*.

6.2.4 The perceived usefulness of real-time viewports and automatically generated drawings

Focus group discussion data reveal that in general the ability to have multiple viewports to display different information is perceived useful. In particular, participants appreciated the real-time correlation amongst the multiple viewports. Analysis of faculty focus group discussion responses, associated with the multiple viewport idea and automatically generated drawings is as follows:

Group I

FM-C: I like the different viewports showing different things (Display01, Display02)

FM-C: Also, the user can customize the window over there, and if you have different views for different fields (performance related fields) I think it would be great.

FM-A: ... being able to pre-visualize in all these representation modes is inexhaustible in its potential...

Group II

FM-H: ... relating formal arrangement to the engineering part of the space... there is also experiential aspect of the space... lots of information that you present at the same time... this kind of tool can be very powerful because at the very beginning you said representation modes influences how we think about spaces, how we think about design... This, because it is so complex, may lead to a different way of designing.

FM-K: ... What I find really, really, fascinating, is you have got this 3D environment... I understand that... students can understand this... If the goal is to get student to understand a two-dimensional abstraction and what it means in a three-dimensional space, now we have a tool we can experiment with.... I think that is a very powerful thing. That you can have them construct some environment in three dimensions and it generates these two-dimensional representations because that is currently the language we are tied to... this as a tool to help people begin to understand what their drawings are representing, is very, very, powerful... That representation bounded by a screen (Display01 main viewport) is not what I see in my mind when I see those things (pointing at Display02 support viewports). What I think what you (pointing other faculty members) are trying to teach in first

and second year is this understanding conception of space. When I draw a section, what am I actually creating.

When the moderator asked graduate students if the real-time automatic generation of the drawing is considered useful, three students nodded in agreement, e.g., four out of the five graduate students interviewed explicitly expressed that they found this capability useful. Analysis of student focus group discussion responses, associated with the multiple viewport idea and automatically generated drawings is as follows:

Group III

GS-C: ... this software is quite useful because after you finish your model, you get all the perspective views, all the renderings, floor plan, sections.

GS-B: ... when you modify design option and I can see it immediately in both section and perspective, I think it is very useful.

Group IV

Sr. C: ... I think moving things are hard to understand something sometimes, but like with these nine visual representation (support viewports), Oh ok I can clearly see how they interact. When it is a physical model you don't have that capability.

So. D: ... I really like the fact that when you change through the different design iterations you can see on all of the different drawings how they transition (a sophomore and a senior student nodding in agreement)

Sr. J: ... cause we tend to work in plan and section and we try to find the best view and this gives you the ability to see every single

section and every single view which, and it is not flat but you can also rotate and I think that's really, really, cool too.

***Sr. J:** ... this could be a useful presentation tool that allows the focus to be more on your experiential qualitative things that are hard to get to in reviews (two sophomore students nodding in agreement). Cause the second they see all these things (the support viewports on Display02) you are always in check. It is either gonna have to work or it will be obvious in the section (that it is not working) (two senior students nodding in agreement) ... so they can focus more on the walk-through or the experiential part of it which I think is a really good thing (a senior student nodding in agreement).*

***So. L:** ... the representation is definitely a good way to fully inform the viewer. Just how in the project you can't really represent the entire project with a couple of images, this is a good way to fully visualize your project.*

***So. M:** The complexity of the drawing... and these sections and these plans, and how they change a long with each other, the experience based thing (Display01), presentation wise... takes away from the "what if" ... that definitely kind of has the viewer almost invested in the project and seeing what they like best and I think it is super interesting.*

***So. Q:** I like how the BIM side of it is really present. The workflow itself speeds it up so much...*

***Sr. K:** I feel like it is a cheat for students so you are kinda designing while in presentation... because I choose the wrong section to represent my project, that's my own fault. Having it set on 2D surfaces (printed drawing) allow students to try to come up with their*

best representation for the project. By doing it in this format... I am able to cheat the system.

When asked about the idea of the multiple viewports regardless of what they represent, undergraduate students responded with the following:

So. A: For sure, I think that is a great idea.

Sr. H: Yes, I think so. For just the viewports (not the content of each viewport, rather it is the idea of the multiple customizable viewports.)

Sr. I: Yes, I think it is good being able to customize the viewports.

So. P: Good.

Sr. B: Yeah.

Focus group data, therefore, confirms that idea having multiple viewports to display different information is *perceived useful*.

6.2.5 The perceived usefulness of integrating performance-based analysis

Focus group discussion data reveal that the inclusion of performance-based analysis is *perceived useful*. Analysis of faculty focus group discussion responses associated with the usefulness of including performance-based analysis is as follows:

Group I

FM-B: For advanced studios that are into this (performance-based analysis), yes. For the practice, yes.

FM-B: ... what performance was and is today or will, that's good... for higher levels and for design... for office or office use, I think it is terrific.

FM-C: ... Some of our clients are mechanical engineering. They would love to see this kind of thing (pointing at Display01 and Display02). And in one of our design reviews, one engineer kept asking: how is the acoustic level? How is the acoustic performance? they are focusing on different things. I think if you can present that, I think that is fantastic.

FM-C: When I saw this tool, these things over here, I thought about a project we have been thinking about for months, using game engine for hospital design... you can arrange all the spaces to see the performance of the building and how to facilitate healthcare. It is really similar.

FM-C: ... if you have different views for different fields (performance related fields) I think it would be great.

FM-D: ... One thing that I like about this is makes visible something that is invisible for some people... you make some decision and it is not visible for clients so, you show just the product or the end process of something. But in this way, you can share the process... I like ... that you see the consequence even as a designer, it is nice to see the consequence on the decision that you made, and you see it in this stage...

Group II

FM-F: ... I can assess what is the value of privacy, or what is the value of solar, or the value of windows...I can plug in one alternative, plug in another alternative and see which alternative I would like ...

FM-F: ... this will be very easy to sell to tenants, it will be very easy to sell to clients... if we can link it to the financial data ... every

time we change one of these things to see what the impact on the different parameters ... impact on the constant, that would be a very powerful development tool.

***FM-J:** ... Now What is really powerful here that we have not talked about a whole lot is the fact that while you are looking at this representationally, you are looking at performance data. That is the contribution....*

***FM-H:** ... the most interesting feature ... or the most useful feature, is the correlation ... between scientific data and the space (another faculty member nodding in agreement). I can easily see how to teach students based on that and do minor design variations and see the effects. ... it is hard to teach them if you have only one existing example and do analysis... they don't see how moving windows around would affect the function or the performance.*

***FM-J:** ... we are all honing on exactly the same thing over here and that is the real standout value is that you are looking at things three-dimensionally, that you can move and change around at will, and you are seeing some representation of data from a more objective analysis of the variables...*

***FM-I:** ... if there is something that we can show them from the technical stand point... it will register then. Those are very technical objective things that could plug in this (pointing at the prototype). Certainly, can plug into the model where if I move a certain architectural things around it is gonna have a direct influence on the experience of the space that these moves will create... get to the sexy view but the building also gotta work.*

Analysis of graduate and undergraduate students focus group discussion responses associated with the usefulness of including performance-based analysis is as follows:

Group III

GS-E: I think this can be like a turn-it-in. I am thinking you are going into a review you have to push your model into this and profs can quickly check. But you know what I mean? This is useful for profs to check and go like: "Yeah but if you go there and there we can see that you haven't designed this very well".

GS-E: ...that would be so helpful for students to incorporate performance and clearly state how this is now.

When graduate students were asked if the inclusion of performance-based analysis, regardless of the specific presented metrics, is considered helpful as they replied with the following:

GS-E: I think it is helpful.

GS-A: Yes.

GS-B: I think you have considered all the aspects of how to show a project.

Group IV

When undergraduate students were asked if the inclusion of performance-based analysis, regardless of the specific presented metrics, is considered helpful as they replied with the following:

Sr. H: Yeah, sure.

So. E: ... it is really helpful ... this tool allows you to see what other options offer. We have not learned a lot about performative

quality but I can see that be very useful comparing when you have different things that you are looking at. Daylight, energy, comfort, whatever and seeing maybe client to client bases what is more important. (moderator clarifying: trade-offs?). Right (a senior as well as a sophomore student nodded in agreement).

Sr. I: Yes, for like the site analysis, the daylighting analysis, instead of using Sefaira... you can see it how it changes throughout the day on the floor plans... I think it is really useful to have it here.

Sr. J: I think it definitely aids decision making in the design process if this is an option... I think it is really good. This tied with the different options and seeing the change.

So. Q: That's where I see the design aspect of this software is being used. Just being able to analyze it and choosing the best one out of that. Rather than choosing something that you already have and analyze it and represent it in real-time... I like that. (The student likes that design options are based on performance and performance is not only reported but also an active part of the design).

Focus group data, therefore, confirm that idea of including performance-based analysis in the proposed PDR interface is *perceived useful*. Participants cited the idea is especially useful for advanced design studios and professional practice.

6.2.6 *The perceived usefulness of the inclusion of multiple design options*

Focus group discussion data reveal that, with some reservations, the inclusion of design options is perceived useful. In few instances, the number of included design options as demonstrated in focus group session was thought to be excessive (10 design options). Analysis of faculty and student focus group discussion responses associated with the usefulness of presenting multiple design options is as follows:

Group I

FM-B: The only thing you want to do is just kind of tweak and show the client 3 design options not 10.

FM-A: ... So, you can use this as a corrective tool for the unruly client. "Yes, we can go ahead and do that, but this is gonna be the consequence..." So, I think that would be useful to sort of rein in the know-it-all client too (The three other faculty members nodding in agreement).

Group II

FM-G: ...I can plug in one alternative, plug in another alternative and see which alternative I would like to present at the end, and then make a presentation....

Group III

GS-E: I think that would be great for when you are making designs and you can... I think reviews, it will become repetitive if fifteen people are presenting all skyscraper for Shanghai. That is how usually studios go, so you will have fifteen versions of that, I think you get depth if you value one that the student has to defend. You can say: "If you had done this you would have had a larger courtyard." You can say but I went through that process, or you can pull it up. Or you can say: "Because that one has more radiation". That is it. I think it is more about proving that you had done it, but generally they kinda believe you.

Group IV

Sr. J: ...I think it definitely aids decision making in the design process if this is an option... I think it is really good. This tied with the different options and seeing the change.

Sr. C: So, what I think is really awesome is you think like you are playing a game but you have so many options and visually it is easier to understand... When it is a physical model you don't have that capability.

A discussion took place in the undergraduate students' focus group session between students for having multiple design options and students against multiple design options. As the discussion evolved, students against multiple design options changed their mind when students for multiple design options, argued multiplicity as a design stance, argument, and strategy. Analysis of Group IV discussion responses for and against multiple design options is as follows:

(Begin dialogue)

Sr. H: I personally think that the student maybe should make the design option and then try to pose that as something that is the best, they think is the best. And put that out claiming this is my design. So, I don't think that for a student in the final presentation they should have these multiple ones and you choose which one is the best. I think the student should have what they think is the best and then pose that. I know that you don't have to have a million design in order to use the software (interface). This is just a way to represent the project with multiple screens and move around it. I think that's really great. As for the fact of having student wise in a presentation having multiple designs, I think that is a cop-out. But for a client I think that would be great. Because they are the ones really deciding not really you.

Sr. J: I agree with what Sr. H said, I think it is great for real world selling to a client not good for students because they shouldn't have that kind of option post it is all set and done. You shouldn't be able to go back and forth.

So. M: It is different in a studio presentation and a client presentation. In a client presentation you, in a way you need them to like it, you need these options. But I think when you are presenting in a studio presentation, it is not so much I want you to like it, its I want you to give me feedback on what I do or don't like... I think there should be one project with one option that represents what I've been thinking about the entire semester exactly. Because I think the excitement of being a student is you're not selling anything. That's what being a student is about. I don't wanna sell anything, I wanna present something. I don't think you need multiple options to represent yourself....

Sr. B: Why does it have to be one? because you have to take a position? Why can't multiplicity be the position?

Sr. H: That would be completely different. Then yes. If that is your argument then yes. If a student wants to have a bunch of different projects then it is ok.

So. E: I think it depends on what you are using it for. I don't think it should be used in an academic setting every single time. But in some cases, for some projects it might be good to have several options. But at the same time not infinite options. There would still be refinement. So, saying it is a cop-out offering things. You wouldn't offer a thousand options. You would refine it down to the three best options that represent what you are trying to say.

(End dialogue)

Focus group data, therefore, confirm that idea of including multiple design options is perceived useful if multiplicity is the argument that guides the project. In general, participants thought the number of design options presented is excessive. However, one faculty member suggested that students learn best through excessive iterative performance-based analysis of many design options.

6.2.7 *The perceived usefulness of animated design option morphology*

Focus group discussion data reveal that the use of animation technique to communicate design option morphology is *perceived useful*. One graduate student cited the moving and rotation of the five boxes may cause confusion. Suggestions were made to diminish the problem. Analysis of faculty and student focus group discussion responses associated with the use of animation technique to communicate design option morphology is as follows:

Group I

FM-A: ...Cause it is so beautifully applicable to this plan based approached you've taken here... The case study that you've chosen is very judicious in the case that you have all these volumes that can rotate and track and everything...

FM-B: ...it is a diagram in motion. So, for commercial purposes, it needs to be very appealing. So, it needs to do that. You need to see the thing moving in real time and all that and say: "Yeah this is cool"...

FM-C: I think that is helpful.

FM-D: That is helpful.

Group III

GS-E: I think once you start flipping through them because turns as well and all of them change, I can't keep track of what it was...I think I can (keep track of the morphology). Maybe max three if they are very different. And I don't know if they are like wireframe of the previous for a little bit longer or it would become smaller so I can bench mark, because you were also flipping before, so I haven't gotten a clue of where I was before.

Group IV

So. D: I really like the fact that when you change through the different design iterations you can see on all of the different drawings how they transition (a sophomore and a senior student nodding in agreement). And can see it when you're standing as if you are there and they are moving (in the main viewport).

Focus group data, therefore, confirm that idea of using animation techniques to communicate design option morphology is *perceived useful* if the technique is further enhanced.

6.2.8 The perceived usefulness of real-time section drawings

Focus group discussion data reveal that the idea of real-time generated section drawings is *perceived useful*. Although the idea of real-time generated drawings is *perceived useful* in general, the real-time section drawings are *perceived* as being particularly *useful*. Analysis of faculty focus group discussion responses, associated with the real-time generation of section drawings is as follows:

Group I

FM-A: ... from the pedagogical standpoint, a lot of our students struggle with where to cut the section, and also the ability to say: this

is my section and this is where it is on the plan, and this is where it appears on the elevation... even though it is a subsidiary function, I think this might be something that this tool can be used for (FM-D nodding in agreement).

Group II

(Begin dialogue)

FM-K: They (students) can model like you would not believe. They have no clue how buildings go together...

FM-G: They cannot make a section.

FM-K: That is happening on the screen too (pointing at the dynamic section).

FM-G: That is the beauty of it.

FM-K: Exactly!

FM-G: I agree with you.

(End dialogue)

Analysis of student focus group discussion responses, associated with the real-time generation of section drawings is as follows:

Group III

GS-D: I think the way you show the section is very useful to me because you can get perspective so I know how it looks like. At the same time, I know that the position where I stand I can get the two sections immediately. I think that is useful for me.

Group IV

So. E: ... it is really cool to be in position where when you change something in plan immediately you see how it affects the section.

Sr. K: ... in terms of relating this to my projects... I provide one section however they wanted to see multiple sections of how my building interacted. Because we print on 2D surface, you can't really get that kind of view of all these other sections. So, with this, and the viewpoint of the character (referring to the experimental section cut) you can get a representation of an unlimited amount of sections and so using this would be very helpful for me. I also feel like the way that this is kinda laid out it is very hard to kinda lie (a sophomore and a senior student nodding in agreement) ...

So. N: ... the dynamic section and the other section (experimental section). I don't know what you would call it, the section where it is oriented with the viewer. You should come up with a name for it. I also think it is very useful.

Focus group data, therefore, confirm that in particular, the idea real-time generated section drawings is *perceived useful*.

6.2.9 The perceived usefulness of utilizing different visualization methods

Focus group discussion data reveal that the use of different visualization communication methods, conceptual, phenomenological, and analytical is *perceived useful*. Analysis of faculty focus group discussion responses associated with the use of different visualization communication methods is as follows:

Group I

FM-B: I would always use it in the none-rendered mode (non-phenomenological visualization method) to really think about mainly

issues of space, in terms of critical issues... Rather than the kind of final representation... the interesting part would be preliminarily before you assign it textures... I will use it in the more abstract mode/spatial mode in this case. The final one (the phenomenological visualization mode) will be good for the client to say: Ok we did this, so you will like this because the sun comes from over here, so you have morning sun in your bedroom, and you like to cook in the morning... and the phenomenological aspect to it. Once that is ok, then you click "Oh there it is!". To me that's something pedagogical more so in the practice....

***FM-D:** ...I think I am with what you said (pointing at another faculty member) without rendering has more performance for the designer maybe. With the render maybe for the client or people that cannot visualize it in the final stage. I still think it has benefits for the designer as well, to see and make it visible that what we decide and how it gonna look at the end....*

***FM-A:** ... being able to pre-visualize in all these representation modes (visualization communication methods) is inexhaustible in its potential... everything happens before the ground is broking on the project.*

***FM-A:** ... we'll start with the Silicon Valley clients, they will get it... they will be like: "Yeah we get this, let's go!". Whereas more conventional modes of representation might be lost on them.*

Group II

***FM-F:** Of course (when asked if he/she would use the tool if available), I've not seen anything like this before. And the stuff that ... did was not as detailed, it was not as close to photo real even though*

we did it in the BIM Cave... there is nothing choppy about this. It has a flow and a navigation, it's quite persuasive.

FM-F: ... the ability to actually experience the place in a semi photo-real with different sensitivities is very powerful.

FM-F: ... but what is useful in this is, and this what I have done with ..., from a developer point of view, this phenomenology component you were talking about, how you experience place, is what determines patterns of repeat visitations, and determines rents.

FM-K: ...That representation bounded by a screen (phenomenological visualization method on Display01) is not what I see in my mind when I see those things (pointing at Display02 support viewports). What I think what you (pointing at other faculty members) are trying to teach in first and second year is this understanding conception of space. When I draw a section, what am I actually creating.

Analysis of student focus group discussion responses associated with the use of different visualization communication methods is as follows:

Group III

GS-C: I think the rendering is very fancy. The presentation is very fancy. But when I worked in china some clients they said the rendering is too fancy, but the actual model is not that fancy. Because of the perspective view and ... do provide the parallel view.

GS-E: When you start walking through it, I was kind of thinking, how would adults feel being in a computer game. Secondly, I was thinking, naughtily thinking, I was wondering if I could shoot someone over there. I shouldn't be thinking that, but it crept in.

GS-E: It has got the feel of a computer game which maybe kids play. Also, for younger people it could be tempting to want to play.

GS-E: I think the solar radiation when it is mapped on the building it is very useful. I have never seen it before. Also, as educational.

GS-E: I think it is useful that it is always at eye level. Because I am thinking this would be technically replacing the model (physical model), and you see often people picking models up and holding them at eye level. Trying to get the scale. I think it is useful for the profs, whether it is more, it doesn't allow students to cheat as much. You know like sometimes you have fancy views from somewhere no one will ever see it from there.

Group IV

So. N: ... regardless of whether or not this will replace paper, I think it necessarily restructures the way in which we design. We say we design in three dimensions and that's why we build models. But when you incorporate the visual effects, sound, this whole immersion experience, I think it is very e-motive and I think that it places a really big role on how we design. So, I think there will be a change in our mind.

So. N: I think the ability to jump between representations remedies the problem actually. It would be better for me, and I think it varies from person to person....

So. N: I think as we were saying, it is successful in the experiential immersion, and the ... of the orthographic views for reference.

Focus group data, therefore, confirm that idea using different visualization communication methods, conceptual, phenomenological, and analytical is perceived useful.

6.2.10 The problem of perceived information overload

Focus group discussion data reveal that PDR, as it was presented in the discussion, may have suffered from information overload. Faculty members had opposing opinions about the amount of information presented particularly on *Display02*. No indication was made that implied *Display01* suffered from the same perceived information overload problem. Analysis of faculty focus group discussion responses associated with the problem of the proposed interface suffering from information overload is as follows:

Group I

FM-C: ...You know looking at the graphics over there (pointing at Display02) they got lost (meaning they would be lost due to information overload) (another faculty member nodding in agreement).

FM-E: ...You have a lot of information particularly these nine viewports on this screen (Display02). The two displays are competing that you almost get dizzy looking at them....

FM-E: ...sometimes it is better to do fewer drawings than many to get your point across...

When participants were asked if the interface suffers from information overload particularly on *Display02*, the following were faculty responses:

FM-C: Yes, on this screen (Display02).

FM-D: Yes (pointing at Display02).

FM-A: To me, because I am a visual learner, images speak to me more powerfully than words do. To me this (Display02) reads like a menu. So, if I am a lay person, one of these images (viewports) is gonna help me understand (snaps finger). You can even say that, so can say: look at this for a little bit, I am gonna show you how it works, and you tell me which one of these views communicates most effectively to you so we can focus on that as we change, as we modify the options in the optimization so... (FM-D agreeing: Yeah)

When the second faculty focus group participants were asked if they easily understood the presented proposed interface, the following were faculty responses:

Group II

(Begin dialogue)

FM-H: I don't think so. I think it is very complex.

Moderator: What is complex exactly?

FM-H: You are relating formal arrangement to the engineering part of the space. Also, you are talking about texture so there is also experiential aspect of the space. I am not saying that complex is bad. It is just lots of information that you present at the same time. Because of that I think this kind of tool can be very powerful because at the very beginning you said representation modes influences how we think about spaces, how we think about design. Using a pencil is different than making a rhino model. This, because it is so complex, may lead to a different way of designing.

Moderator: Do you think there is an overload of information?

FM-K: It is very dense.

*FM-H: To me it is marginally overload... I am single minded.
When there is one thing I would like to focus on it. But maybe here it is
different.*

(End dialogue)

Analysis of student focus group discussion responses associated with the problem of the proposed interface suffering from information overload is as follows:

Group III

*GS-B: When I was seeing the 9 viewports I felt confused. It is too
much information on one screen.*

*GS-E: ...I can see student got massive dilemma, do I prioritize this
or that. And then you got the two options and you can see the tradeoffs
and make the argument that way. Whereas if you are showing sixteen,
it is so many that you are still designing.*

*GS-C: I don't think it is too much information. But for the ten
options, they are quite similar I think. So, if you are walking through
the area you cannot tell the difference, maybe in the floor plan you can
tell the difference. If you are walking through the building you will feel
lost.*

*GS-C: One thing I want to say. I was swarmed by too much
details. It is hard for me to get the whole picture... Yes, many
drawings help me to know the many details of the design but too many
details. I am lost in some of the details.*

Group IV

When undergraduate focus group participants were asked to raise their hands if they thought there is too much information, nine people out of sixteen raised their hands. Four of which were senior students and five of which were sophomore students. Students that did not raise their hands expressed that there is a need for more information.

Sr. B: I think it needs more.

Sr. H: If you've been in an integrated review it is more than that.

It's like everything!

When undergraduate students were asked if it would be useful to extend the interface beyond two display multiple senior and sophomore students agreed verbally or by nodding.

Focus group data, therefore, suggest that PDR, as it was presented in the discussion, may have suffered from information overload. Group IV did not unanimously agree that the interface, as presented in the focus group session, suffered from information overload. Similar to faculty members focus group participants, some students felt there is information overload suggested that *Display02* is the cause of the problem. Other students felt the inclusion of many design options may have caused the perception of information overload. Undergraduate students were split where some felt there is too much information while others felt there isn't enough information.

6.2.11 The potential of PDR interface as a replacement of paper-based design reviews

Focus group discussion data reveal that PDR has the potential to eventually replace paper based-design reviews. The question was only brought up *Group IV* with the undergraduate students. Opposing view point emerged during the discussion. However, most students thought in the future when appropriate high-resolution displays become ubiquitous; it is possible that a variation of PDR method may replace current paper-

based design review methods. Analysis of undergraduate students' focus group discussion responses associated with the potential of PDR to replace paper-based design reviews is as follows:

Group IV

(Begin dialogue) (End dialogue)

So. A: I think it can replace it right now. If you get the screen and the ability to have screens everywhere. Yes.

So. E: In this time in architecture, you have different ways of practicing where there are people who are not ready to adapt to something like this. Yes, for us coming up, but the practice as a whole no.

So. O: I think of course it will replace the paper. In paper, you cannot see the changes in the section instantly... Obviously, I feel like it is gonna change.

Sr. J: Yeah, Yeah, if the screen can have stills (still representations) then yeah it can replace it... yes, a screen can replace paper.

Sr. R: I don't know I think there is substance to printed that would never leave...

Moderator: Before we jump around. What if you had a super high-res projector, and through which you project the unrolled pano? You can see all the details. Similar to the printed. Would you still say the same thing or would you change your mind? Is the value in the paper itself?

Sr. R: ...I think it is a tangible thing. Because I've also hated when the people present on the big screens in the glass box. I just have never been a fan of it. Cause I think there is something nice about the printed object.

Sr. H: ... kids now they go to school they have iPads, we grew up with paper so we are used to that? We are used to books, but they have iPads. It is already going.

Sr. H: ...I think the nostalgic paper and the quality of it, I think those desires might diminish over time. For us, I would still rather have the paper but I don't think kids right now would think so.

Sr. J: I think it has the potential to replace.

So. F: I don't think it will ever replace paper. Like with 3D printed models right now we are just using that to enhance our projects, so I think this could enhance it but not replace it.

Sr. B: What if the presentation boards are on panels that have integrated screens so they can barely tell the difference between the pinned drawing...Here you see the screen (the proposed PDR interface) as an object and you're like, ohh future (expressing disgust). What if in the future the screen is part of the wall and the way you perceive posters is the same.

Sr. J: ... thinking about materiality, when you see a render on the screen vs print there is something more tangible about a print because material in the real world doesn't have brightness behind it... it depends on the drawing. I feel like if it was a plan in that kind of graphic style (pointing at Display02 support viewports) you can totally replace it with a screen why would you even print it. I feel like it could depend like drawing to drawing.

So. E: I think your argument about screens is very interesting and it makes me think of when the kindle just came out. They didn't have backlit screens but they were still digital. I know it doesn't have the capability to project this type of stuff (pointing at PDR) but I think it could transgress to that.

Sr. B: Also, what do you do with the paper afterwards?

So. E: Look at ... all of that paper that is thrown away when we cut... with the change in here (PDR) we wouldn't waste all the paper.

Sr. B: You also have to wait on the print...

(End dialogue)

Focus group data, therefore, suggest that the proposed PDR interface may eventually become a replacement for paper-based design reviews when capable and appropriate display systems become ubiquitous.

6.2.12 The potential of PDR as a design tool

Focus group discussion data reveal that PDR might have the potential to be used as a design tool although it was conceived as design review tool. Faculty members had strong opinions about whether or not PDR may be considered a design tool. Some faculty members strongly opposed the idea, while others embraced it. However, the discussion reveal that the inclusion of different evaluation modes offered by the proposed interface in design software is desired in general. Analysis of faculty focus group discussion responses associated with the potential of the proposed interface to be used as a design tool is as follows:

Group I

FM-C: ... I am still arguing, whether this one is a really good design tool or design representation thing. I think this is a good design tool for, especially for participatory design...

FM-B: ... it is not a design tool. But to verify things that have been established before. The risk for me is that you begin to think that it is a design tool just because you move the boxes around, so you're designing... But the idea is really not. It is that already that has been predetermined.

FM-C: ...It could be a design tool though. Just so many options Site planning but also different configurations of the space inside as well.

FM-B: ...I am sort of nervous calling it a design tool... it is really about testing design options. "Testing" (emphasizing)... it used different modes of representation to test that idea. So performatively does it work best? The light, etc... these kinds of thing. So, you are requesting your client or your team to be responsive to this idea of optimization. To me that's really what it is. Because I think there are many design tools, or whatever, so this will be another design tool? ... it is more of cooperation, optimization, presentation, and representation. These are to me the kind of things that this thing (referencing the interface) can do very well.

FM-B: ... we should refrain from thinking of this as a design tool, it is an evaluation tool. And the motion is just to articulate what has been decided. (another faculty member nodding in agreement).

FM-B: I think it is really good. I think it is an evaluation tool. I don't want to call it a pedagogical tool. That is my reservation. It is not a tool to teach anybody design or architecture.

Group II

FM-G: I see it as a tool. I see it as a practical tool... very practical. But I see it also as a tool for design studio....

FM-J: Let's make a distinction over here between something being a design tool, as means of exploration, and something being presentation... It is an alternative way of presenting. As far as making design decisions are concerned, at this point in time it is virtually useless. Because of the effort involved...

FM-G: ... I can see that right now it is a presentation tool but I can see it easily developed into a design tool, exploratory because if I design something and I can assess what is the value of privacy, or what is the value of solar, or the value of windows it becomes also a tool of design decisions. I can plug in one alternative, plug in another alternative and see which alternative I would like to present at the end, and then make a presentation. So, I can see it being not only just as presentation tool...

In student focus group discussions, students expressed the potential of PDR as a design tool implicitly and explicitly. Analysis of student focus group discussion responses associated with the potential of PDR to be used as a design tool is as follows:

Group III

(Begin dialogue)

GS-D: *I wonder if I bring three design options to present to my professor. My professor says, I don't like the second or third one, I like the first one. But I want to move the door and window a little bit, can I show my professor immediately if I move the door and window how will the light change and all the things will change? Does it work... I don't mean in the final, but in the middle. I want to show my design to my professor in this way and if it can be modified or revised immediately it will be great. So, every class I can bring this presentation, not the final*

Moderator: *So, you are saying during the process, it would be great if we can change things. So, if this was inside Revit, for example, and you can have all this graphical capability plus the change and the modeling ability, it would be great.*

GS-D: *It will be great I think.*

(End dialogue)

Group IV

So. F: *I think this is a great design tool... I can see this as a plug-in for design software and be able to walk through the building... the ability to see it in real-time when you want to change some stuff.*

Sr. J: *I think it is a cool design tool, but also as a method of representation for people seeing the building. Just cause we tend to work in plan and section and we try to find the best view and this gives you the ability to see every single section and every single view which, and it is not flat but you can also rotate and I think that's really, really cool too.*

So. Q: I like how the BIM side of it is really present. The workflow itself speeds it up so much. As it is I don't see it as a presentation tool, more of a design and production tool producing all these plans and scenes from this one model...

Focus group data, therefore, suggest that PDR may have the potential to be used as a design tool in addition to design review tool. Participants suggested that a live connection with or embedding PDR in a design tool, such as Revit or Rhino, would be useful.

6.2.13 The potential of PDR outside of academic settings

Focus group discussion data reveal that in general the ideas demonstrated using PDR are *perceived useful* beyond academic settings. Faculty members and undergraduate students thought the tool may be useful for architectural professional practice. Analysis of faculty focus group discussion responses, associated with applicability of PDR outside of academic settings is as follows:

Group I

FM-C: ... Specifically, for design review. I think that it's a fantastic tool if I have all those clients, real project, they have that kind of tool during the design review, I think that is great.

FM-B: ... So, this is for higher levels and for design, or you know, for office or office use, I think it is terrific.

FM-B: ...I am constantly referring to practice because I think this is where the application is mostly needed

FM-C: ... not only architecture students/professors. I have a lot of clients, they are lay person. You know looking at the graphics over there (pointing at Display02) they got lost (another faculty member nodding in agreement) ...for participatory design... our clients are

mechanical engineering. They would love to see this kind of thing (pointing at interface prototype) ... in one of our design reviews, one engineer kept asking: how is the acoustic level? How is the acoustic performance? they are focusing on different things. I think if you can present that, I think that is fantastic.

FM-B: *... The final one (the phenomenological visualization mode) will be good for the client to say: Ok we did this, so you will like this because the sun comes from over here, so you have morning sun in your bedroom, and you like to cook in the morning... and the phenomenological aspect to it. Once that is ok, then you click "Oh there it is!". To me that's something pedagogical more so in the practice... it will educate the client in a lot of ways of the design thinking that the architect goes through in order to make a certain decision, and finalize that. So, it is educational in a sense because they will be: "Ok now I get it why you go through all this stuff" (Meaning, bring value to architecture because architects are being undermined).*

FM-B: *I keep on going to the practice and thinking that this is a fantastical spectacle for the client. Because for an office it is not expensive to buy these TVs. And show them (the client) the difficulty of doing architecture: "Ok this is a drawing and it happened like that (snap finger)". But no, we took a lot of things into consideration. (another faculty member Nodding in agreement).*

FM-A: *... it is a really important tool for reasserting the importance of the architect (another faculty nodding in agreement).*

FM-B: *I think these are the things for me that I really think we are in a critical situation in relation to that (the clients devaluing the works of architects)... it is obvious the benefits academically, for a*

studio or an integrative studio... in the practice, internally with a team within an office, it is good ... also the projection it has to demonstrate to the client the importance of architecture to assert your decision and the difficulty and challenges that you face in trying to resolve the project. And not thinking: "Oh it is just so easy". Which is something that happens with clients and they don't pay.

***FM-C:** ... a project we have been thinking about for months, using game engine for hospital design... It is really similar.*

***FM-A:** ... we'll start with the Silicon Valley clients, they will get it... they will be like: "Yeah we get this, let's go!". Whereas more conventional modes of representation might be lost on them.*

***FM-B:** Honestly, I think you should also show it in offices. HKS, John Bailey, healthcare. Showing it to that community is quite important.*

***FM-B:** The thing we were arguing is that it is not only good for academia, but also very good for practice. Sometimes when you are presenting you have to show the client things, and educate them at the same time. Because they begin to see the effort that you go through to do a floor layout, or things like that....*

***FM-A:** if someone acquires your idea and develop a plug-in for all the design tools will be great.... The irony is that you developed a tool which is a plug-in for digital design suite that reasserts and even increases the importance of architecture through the process. Cause a lot of time people are afraid that pretty soon you just type what you want and an Autodesk product will design the whole thing. But this, is the opposite of that. It is saying: " This is why you have to have the architect."*

FM-B: Anything at this point in time that reasserts the role of the architect and evaluates their job is super good.

FM-A: ... there is a conference on digital heritage and I think this would be interesting for people who interested in the virtual heritage realm will be very interested in... I think this would be a good tool for that as well....

FM-A: ... even in the pedagogical sense it reasserts the importance of the architect.

Group II

FM-F: ...I am not an architect, I am looking at this from the point of view of a developer... what is useful from a developer's point of view, this phenomenology component you were talking about, how you experience place, is what determines patterns of repeat visitations... the ability to actually experience the place in a semi form (final?) real with different sensitivities is very powerful... this will be very easy to sell to tenants, it will be very easy to sell to clients... if we can link it to the financial data ... that would be a very powerful development tool.

FM-F: ... From the developer's point of view... I am looking for a tool where there is multiple of sensitivities... design is a tradeoff... if I can see what the tradeoff is I can begin to understand what the cost and benefits are of a particular solution... From the point of view of the consumer... they are always looking for is a good fit between what they are looking for from the place and what's available to them. This is a great tool to give an almost photoreal experience to them... I have been looking for a long time now for a tool that allows me to trigger all five of the senses... I think you could do that with this tool and I think it would be very powerful... every person in the world can tell

you whether they like that place or they don't like that place... that is the decision that is important to us as a developer... if they like it we can rent it, we can sell it...

FM-I: I agree... from the business perspective. The client sees this and think "it is sexy". If it looks good, if they like it, if it makes them feel good, if I can see the shadow on the ... " Oh wow, my building will look like that". Then yes....

FM-J: My gut feeling is that it is good... I may not use it for what you think, I may use it for demonstration. I may use it for an entirely different thing... I would use it for something that is totally foreign to what generated it.

Group IV

Sr. H: I think it is really great for the practice and the client... as architects we can understand things in plan and section and begin to visualize the space (mentally). But I know that other people are not trained like that... these kinds of possibilities for them would be really helpful. Having quick changes and different possibilities you can cater to what they want would be really crucial in the practice... for the practice I think it is something that could be really, really great. Especially having something that different views (pointing at Display02) and the 3D model (Display01).

Focus group data, therefore, suggest that PDR may have the potential to be used outside of academic settings, specifically, in architectural professional practice as a tool to demonstrate multiple design options to clients.

6.2.14 The importance of perceived ease for potential users

Focus group discussion data reveal that the *ease of use* is important although no testing for *ease of use* was conducted. Analysis of faculty focus group discussion responses associated with the importance of the *ease of use* as a deciding factor in adaptation is as follows:

Group I

FM-C: I have a question. How much time did it take to generate this? Under 25 days? ...Because generally we have 12 weeks for design studio, right? Sometime 13 weeks. The students if they have not learned that before, and how much time do they need to learn that, and how much time do they need to spend on generating that kind of different models? And do the analysis. Even for the integrated studio, the comprehensive studio for the grad students. That would be the time that concerns the instructors.

Group II

FM-F: How long did it take you to do this?

FM-F: So how transferable is this from one design to another?

FM-G: ... I am only questioning the learning curve to know how to use it in the most effective way.

FM-G: ... The only question is of the learning curve, how much it takes to really be proficient in this kind of tool.

FM-I: ...how long would it take to generate something here that would be profitable, feasible, won't hurt the fee? I am sorry I am a real-world person.

FM-F: ...but that assumes what I get to actually show people is feasible. As in my colleague's view, if you give this Lamborghini to a two-year-old, he will crash that thing.

Analysis of undergraduate and graduate students focus group discussion responses associated with the importance of the ease of use as a deciding factor is as follows:

Group III

GS-C: I wonder how tough is it to use this software? Because I wonder what's the base and how do I put the model? How to handle the views? And what are the requirements for the computer quality (specs)?

GS-D: I wonder if I bring three design options to present to my professor ... But I want to move the door and window a little bit, can I show ...immediately if I move the door and window how will the light change and all the things will change? Does it work.

GS-D: ... I want to show my design to my professor in this way and if it can be modified or revised immediately it will be great. So, every class I can bring this presentation...

GS-C: ... I only wonder about how much time it will cost to make this.

Focus group data, therefore, suggest that the *ease of use* and adaptability of PDR are important for potential users. The importance of *ease of use* may be inferred from implicit and explicit responses.

6.2.15 Suggested enhancement to PDR

Focus group participants provided many note-worthy suggestions for enhancing PDR. Some suggestions were made regarding enhancing existing functionality while other proposals were made for added functionality. Similar to the above constructs,

suggestions were categorized by the author into several points. Suggestions made by focus group participants will be considered for future work. The following is a discussion and explanation of the suggestions:

a. The ability to minimize, maximize, or hide a support viewport.

Participants in every focus group session have commented on the excessive number of support viewports on *Display02*. Multiple participants suggested that it would have been useful to be able to minimize, maximize, or hide support viewports during the design review. Analysis of focus group discussion responses citing the usefulness of the ability to minimize, maximize, or hide support viewports is as follows:

Group I

FM-D: Do we have option minimize it? Because for me I have two option: a section or plan, can I pick which do I want to see? Can I do that? or is this fixed to 9?

FM-C: So, you can double click it and enlarge it.

FM-D: So, if this is could be interactive it means I can click on one (support viewport in Display02) and blow-it up, and go back... so I can switch between different screens (viewports). I think that could be really important so that if I want to check the section I go to the section and enlarge it and go back. (two other faculty members nodding in agreement)

Group IV

(Begin dialogue)

So. N: ...It would be better for me, and I think it varies from person to person, if I could just see one or two views and then be able

to see additional information when I want to. (one senior nodding in agreement)

***Moderator:** So, for example, if let's say you have the ability to maximize the floor plan, and have this (Display01) and just the floor plan. Then go back and you wanna see the section, minimize the floor plan and maximize the section. Stuff like that, is that what you mean?*

***So. N:** Yes! (another senior student verbally agreed while three seniors and several sophomores nodding in agreement)*

(End dialogue)

***So. L:** ... I guess just the map (mini-map) viewport if you can hide it.*

b. Generality and adaptability to diverse building typologies and scales.

PDR was developed with the HFT test case in mind. Therefore, features such as animated design option morphology were chosen due to the applicability of such techniques to the scale and parti of the HFT. While participants appreciated the specificity of PDR in relation to the HFT, at the same time they hoped for additional examples that demonstrate generalized approaches to communicate design, and design option morphology, for different building typologies and at various scales. Analysis of focus group discussion responses suggesting further generality and adaptability to diverse building typologies and scales is as follows:

Group I

***FM-A:** The case study that you've chosen is very judicious in the case that you have all these volumes (the HFT concrete boxes) that can rotate and track and everything. For a single volume, is it going to be equally spectacular do you think?*

***FM-B:** What he is saying is something interesting. You are privileging the plan. It is plan privileged. And to me that's a problem because let's say you are dealing with a theater. And you are showing this with a theater. That is a sectional problem by its nature. Or any other architectural problem that is based on massing or section. So, the tool has to be, not presenting as privileging the plan, and the compositional aspect of the squares, that's why he said very judiciously that selection. Because it lends itself to this. But when you are talking about a mass, one single mass that is complex, or the discussion in the studio or in the office with the client, is a sectional problem, I think it is also, making sure that it is also for all those things (sectional, massing, plan).*

***FM-A:** The one thing I would like for you to consider but not necessarily produce is: think of a volume to which this particular evaluation tool seems least applicable. Cause it is so beautifully applicable to this plan based approach you've taken here. Because I think, in terms of pushing, pushing, it addition to thinking of more complexity, soil condition, seismic conditions, and all that stuff that you can use, I would like to also narrow it down. For example, how to design a traditional Japanese tea house, which is a tiny space not too complex at all. I want to evaluate my choices using this tool. Because to me, if it works at that scale, and at this scale and beyond, then you did good.*

***FM-B:** I think you should evaluate it at a large scale. Because if you are gonna use this for a hospital, then most probably you will be going floor plan by floor plan. Maybe there is evaluation for the mass and volume separately. And there is another one that is floor plan driven, or areas. programmatic area driven of the project.*

FM-A: ... The other thing that I would suggest concerning future work because I am a historian. I see this as an amazing tool for history... So, as a way to teach history through design, and design through history, I think this could be a great tool as well. And the risks to the aesthetic intuition of the architecture student is not that great, if you are using it to facilitate the understanding of the experience outside of the US especially. Something to think about for future work.

c. Integration of PDR in design tools for real-time evaluation of design decisions.

As discussed above, many participants hoped for an integrated environment where PDR may be embedded within a design software, e.g., Revit or Rhino. This ability was suggested due to the perceived usefulness of PDR as a design tool in addition to being a design review tool. It also was considered a convenient solution where a live connection between design software and PDR will instantaneously allow for personal design evaluation before committing to design options for design reviews. Analysis of focus group discussion responses suggesting a live connection between a design tool and PDR, or embedding PDR within design tools is as follows:

Group I

FM-A: I am also interested in this tool, for future work, as a way to teach consequences of design decision... So, this, has the potential to, in the later stages of the program, to teach in real-time, hyper-real-time, the consequences of certain design decisions. So, it would be really interesting (another faculty member nodding in agreement).

FM-A: ... then you make it as such that I can expand the thickness of my walls, change everything related on the materials that I'm using (pointing on Display02). Introduce all these passive climate responsive features. And everything happens before the ground is broking on the project.

Group III

GS-D: I wonder if I bring three design options to present to my professor. My professor says, I don't like the second or third one, I like the first one. But I want to move the door and window a little bit, can I show my professor immediately if I move the door and window how will the light change and all the things will change? Does it work... I don't mean in the final, but in the middle. I want to show my design to my professor in this way and if it can be modified or revised immediately it will be great. So, every class I can bring this presentation...

Group IV

(Begin dialogue)

So. N: I think as we were saying, it is successful in the experiential immersion, and the ... of the orthographic views for reference. However, it is not fully real-time as you were saying so I don't think that it is very adaptive in a sense because you have already loaded these ten parametric models so you have chosen these things. So, if I for instance wanted to change a material quality or change the way a massing is positioned, maybe not the position, but the form of it, I cannot do that.

Moderator: So, if this was inside Revit for instance. All this high-end graphics and the ability to have multiple viewports that change live, whatever, would you be happy?

So. N: Happier (multiple students nodding in agreement).

(End dialogue)

Sr. K: For the viewpoints that we see at the bottom and the elevation and the two top views. Are those views that you set in here or is it views that you set into Rhino and import here and it transfers it.

d. *Integration of VR, AR and AI into PDR.*

Focus group participants suggested the extendibility of PDR to include VR or augmented reality (AR) visualization methods. An interesting suggestion had been the inclusion of artificial intelligence (AI) as an active evaluator of design projects. The inclusion of AI is not meant for the evaluation of quantitative performances as that is introduced in the prototype via Pareto Optimality. Rather the suggestion of using is meant to evaluate a given design option qualitatively. Analysis of focus group discussion responses suggesting the inclusion of VR, AR, and AI is as follows:

Group I

FM-B: Or maybe the next thing would be VR actually.

FM-A: VR/AR and AI maybe. Not to give AI the design and let it do the design, but allow the AI to process all of the permutations, the algorithmic possibilities. and then Pareto optimization will be part of it. Then you can say, the architectural professor can evaluate the project and say: "This is how I evaluated your project. Let's see how AI will evaluate your project."

e. *Inclusion of scale figures to indicate scale*

A participant felt that the inclusion of scale figures in the *navigation evaluation mode* may aid in comprehending the scale of a given design project. PDR currently relies on furniture, texture, vegetation, and fenestrations to communicate scale. However, when using the *conceptual visualization method*, all elements that may imply scale specificity are hidden. Thus, a suggestion was made to include scale figures in the virtual environment to aid in comprehending the scale of the given project. Analysis of focus

group discussion responses suggesting the inclusion of scale figures within the virtual environment in the *navigation evaluation mode* is as follows:

Group III

GS-C: Maybe for this building I think it is ok because it is small scale. But for a high scale building you will feel lost scale. To put some people in, to remind people of the scale... Perhaps for right now it is small scale. But if you are building a skyscraper and other designs don't have doors or furniture, you just walk around environmental, it will be easy to lose scale without people. Not only people because you can have scale items. Because for people who do not like to put furniture inside, especially for preliminary design.

f. Inclusion of a comparative mode and score system for reported performances

Participants suggested that while the *dashboard evaluation mode* was useful, it lacked a comparative or a rating method. A *comparative method* was proposed to facilitate comparing the performances of two design options side by side. A rating score system was also recommended so that the *dashboard evaluation mode* does not give numerical feedback of metric but rather a score. By using a scoring system, participants suggested that it may be easier to compare and therefore comprehend the performance of design options. Furthermore, a scoring system may make it easier to communicate performances to lay persons. Analysis of focus group discussion responses for the inclusion of a comparative method and a scoring system for reported performances in the *dashboard evaluation mode* is as follows:

Group III

GS-E: ... Maybe max three if they are very different. And I don't know if they are like wireframe of the previous for a little bit longer or it would become smaller so I can benchmark, because you were also flipping before, so I haven't gotten a clue of where I was before.

***GS-B:** Because you are presenting your project in a student perspective, and when you are presenting there might be some professors, some experts, to evaluate your design. Maybe different people will have different opinion of your design. Also, you show some evaluation standards. What if someone likes the first option and someone likes the third option and if you really need a decision, and which one do you wanna choose. I wonder if there any possibility that you can.... Because you have three hmmm. You have total solar radiation, and there will be a number. If there is any possibility that this engine can give this number a score, and then it will give people a standard. Because you have three evaluation standards maybe the engine can give you the total score, then maybe help people have a decision.*

***GS-A:** I think we need some windows for comparing options....*

Group IV

(Begin dialogue)

***So. E:** While I appreciated the ability to transfer between designs I really wished there was some type of viewport that showed them next to each other. So, we like these two, juxtapose plans.*

***Moderator:** So, a method of comparison?*

***So. E:** Yes, maybe with four screens.*

***Moderator:** What if this screen (Display01) would split and show you this is this design and this is this design (side by side comparison)*

So. E: Or if this screen (Display01) show a different design option in that layout (Display02). So, you have nine (viewports) of design option 1 and nine of design option two.

(End dialogue)

g. Route suggestions for navigation evaluation mode

PDR provides complete navigational freedom to the user while in the *navigation evaluation mode*. A participant suggested that the inclusion of suggested routes may aid in better navigation of design options, especially for large-scale projects. Analysis of focus group discussion responses for *suggested routes* in the *navigation evaluation mode* is as follows:

Group III

GS-C: ... for the movement, if you move by yourself the line will be curved. Because in the movement you will lost your direction, you will go back and forth. Maybe you can give suggestion routes go to your design parti area.

h. Ability for creating still representations via snapshots

A suggestion was made to include the ability to take snapshots during the design review. The idea is that once the information in certain viewport, main or support, is considered useful during the design review, the user may take a snapshot of that viewport. This snapshot can then be included to the interface as yet another support viewport. For example, if during the design review a certain section cut becomes important for the discussion, the user may take a snapshot of the section and include it as a separate non-dynamic viewport. Analysis of focus group discussion responses suggesting the ability for creating still representations via snapshots during the design review is as follows:

Group III

(Begin dialogue)

GS-B: Maybe when you get one step and the professor likes the section and he wants to leave a memory and then you pull the section out into a static way

Moderator: Basically, taking a snapshot? So, as you walk-through, you say: Ok I like this section so I take a snapshot of it? (Four participants nodding in agreement).

(End dialogue)

i. Ability to explain design process via animation technique

Some design studios require that students explain the design process and how the formal attributes of the design project were developed. Therefore, participants suggested that it would be useful if PDR included the ability to communicate design process. When the moderator suggested the use of animation techniques such as ones used to convey design option morphology, many participants showed enthusiasm towards the idea. Analysis of focus group discussion responses suggesting the inclusion of methods for explaining design process is as follows:

Group III

GS-E: ... So, you can say I started with this, and then I split the building in half. Then I ran solar radiation and this is awfully exposed, so I am gonna subdivide it. Then I looked at privacy so I took these three steps. Then I realized I don't have any courtyard, so I shoved it.

GS-E: ... How you got where you are, and what you've abandoned and how you moved forward. They didn't want to know about all the decisions, just wanted to know about the big ones that you took

GS-E: Sequences yes. I think that would be so helpful.

GS-D: ... It didn't show the process of my design. All of it is outcome. I want to show to the professor how I generated this design. Why I choose this one option vs the two option. I want to show him the parti or something to show him how the process of this, diagrams.

j. *Orchestrated immersive walk-through slideshow*

As a solution to the problem of information overload caused mainly by the nine support viewports on *Display02*, one participant suggested the use of a hybrid technique to arrive at an orchestrated immersive walk-through slideshow. The idea is that PDR would have the ability to display support viewports sequentially and based on the designer's narrative. Analysis of focus group discussion responses suggesting an orchestrated immersive walk-through slideshow is as follows:

Group III

(Begin dialogue)

Sr. J: ...I think it could be a very powerful design tool by strategizing your presentation to have a walk-through window with a certain view as you have explained (on Display02) a certain aspect of the project and then moving to a new window where it has other, maybe more energy analysis, where you can describe more where you are in a project with the J-cut (the experimental user point of view section cut). I think if you strategize your presentation chronologically to show different sets at different points, it becomes a very powerful presentation tool... less than the design changing itself. I am talking about having a walk-through with the floor plan for a while, then as you explain more about the project, you have the first ones go away and other windows pop-up. So, it gives you an opportunity to present it

at a slower pace, but you still see those windows. Maybe not all at once.

Moderator: So, based on where you are in the presentation, certain information hides or disappears. And you move to the next step. Let's say the next slide, and you get three windows. Then you move to the 3rd or 4th slide and you get only one or two windows. Is that what you mean?

Sr. J: Yeah.

(End dialogue)

k. Labeling the experimental section-cut in plan

Live support viewports section cuts A and B were labeled on the floor plan viewports. However, the experimental user-point-of-view section cut was not. Although students were able to comprehend how it works, some felt that it may be necessary to include the label on the plan to avoid confusion. Analysis of focus group discussion responses, associated with labeling the experimental section in the floor plan is as follows:

Group IV

So. Q: It might be a small thing but the J-cut (experimental user-point-of-view section cut) in the plan is not represented. If it was it would be a lot easier to see. (three sophomores and one senior students nodding in agreement).

l. Diverse visualization communication methods/styles

The diversity of visualization communication methods/styles is implied in PDR via the three included visualization methods (conceptual, phenomenological, and analytical). Nevertheless, the comment brought up by students imply that there is a need for more diverse visualization styles that may accommodate to different artistic expression and

design philosophy. Analysis of focus group discussion responses, associated with including diverse visualization communication methods/styles are as follows:

Group IV

So. J: ... maybe a viewport that can spin or kinda like the interactive walk-through that is more like a traditional drawing style. Less rendered with more gradients of hatching and shadows. More like a black and white drawing style.

m. Weathering, decay, and occupant space intervention

A deliberate effort was made to simulate all the subtle imperfections and minor decay observed in the HFT test case used to demonstrate PDR. However, participants wondered if more severe weathering may be included as an inquiry into the future of the design project/option. Other participants discussed the possibility of occupant space intervention citing the problematics of pristine renderings used for marketing that usually do not resemble the realities of living in a space. Analysis of focus group discussion responses, associated with including further suggestions of weathering/decay and occupant space intervention is as follows:

Group IV

So. N: I also think it might be useful to portray the arrangement of buildings in a variety of environmental situations. We see this romantic version of this building, it would be interesting to see how this building age over time. Or to see like a hurricane.

Sr. R: ... What about how the project itself becomes overtime. Right now, the renders are clean and pristine like you just moved in. But what can I do with the space in between. Like how one configuration is better than the others? Just because I like it or what can.

Sr. R: ... *Weathering or just people put something on the exterior of the building. Swing set or whatever. So why one configuration, just because I like it or because for future it would be better than another one. I might be a little ambiguous.*

Sr. R: ... *When I started thinking about the question I was gonna ask. Cause right now when I see the realistic render everything is like neat and pristine and you have these trees. But that's sometime, architecture is represented weirdly. That's why sometimes photorealistic renders are controversial. It is not always gonna look like that. What would happen to everything overtime, is it still*

n. Live clipping plane in the navigation evaluation mode

This functionality was indeed planned for PDR but was not included in the presented prototype. The idea is that the user would have a live clipping plane that may be manipulated during the walk-through, and the results of this manipulation will be evident in the main viewport. Analysis of focus group discussion responses, associated with including a live clipping plane in the navigation evaluation mode is as follows:

Group IV

So. P: ... *Would you be able to get a clipping plane type in the 3D?*

o. Layering or decoupling of, the analytical visualization method and the phenomenological visualization method

Students expressed that layering transparent information on top of the *phenomenological visualization methods* may be helpful. By layering information or simply adjusting the transparency of the *analytical visualization method* on top of the *phenomenological visualization method* users will be able to spatially comprehend the layered information and/or analysis. Furthermore, it was implied that layering the information may cause less cognitive burden than the instantaneous switching between the two modes. Alternatively, another student suggested the decoupling of the different

visualization methods from *Display01* to other displays for simultaneous *navigation evaluation mode* of the three *visualization methods* to multiple displays. Analysis of focus group discussion responses, associated with layering the *analytical visualization method* on top of the *phenomenological visualization method* and the decoupling of *visualization methods* is as follows:

Group IV

So. E: I was gonna say if you have structural analysis or systems analysis, could you have ghosted representation? It would be more useful, as a suggestion.

So. A: I would like to see a cross representation with some overlay of information especially in this viewport (the analytical visualization mode). Maybe have the render behind it and this ghosted over it just to kind of understand what you are looking at. Instead of having to switch back. Be able to have that information on this part just so that you know exactly what you are looking at. Cause this has clearly a lot more information to that. This is just a box. Something that you could toggle on and off.

(Begin dialogue)

Sr. J: Also, even if I could have three screens and have that (the analytical visualization method) and have three options as I am walking through in the three formats (the different visualization methods).

Moderator: So, the different formats (Visualization methods) as support viewports. Big support viewports.

Sr. J: Yes.

(End dialogue)

p. Extensibility to more displays

Group IV

When students were asked if they would like to have a large number of displays when using the interface, the answer was a unanimous “Yes.” One student referenced the BIM-CAVE.

6.3. Summary

Focus group experiments with faculty members, graduate, and undergraduate students were conducted where PDR was demonstrated. Explanation of focus group experiment was provided as well as results and discussion. Also, suggestions made by focus group participants were included for a comprehensive analysis of the experiment.

7. DISCUSSIONS

As mentioned in the *Literature Review*, Kalay (2004) uses six points to discuss changing communication and representation in architecture due to the advancement in computer technology. Kalay expresses the possibility of changing communication and representation in architecture due to the advancement in computer technology in the following properties of modern computers: flexibility, interlinking, information management, visualization, intelligence, and connectivity. This chapter is an attempt to establish a theoretical link between the PDR, as demonstrated in the focus group interviews, and Kalay's six points. Below is a summary of how PDR addresses the possibilities of each point.

7.1. Flexibility

According to Kalay (2004), flexibility can be defined as “the ability to change levels of abstraction as needed without having to reconstruct the representation from scratch”. Similarly, the PDR prototype suggests a level of flexibility, which may be developed even further, for design reviews. For example, the ability to change the level of abstraction in the main viewport as well as viewing different levels of abstraction for the individual support viewports. In the main viewport, the designer may cycle from conceptual, to phenomenological, and to analytical visualization methods, at will. In the support viewports, a juxtaposition is introduced where for example there are two types of dynamic plan drawings: one that is textured and rendered using conventions of interior design discipline, and another that follows the conventions of architectural drawings (Figure 7.1).

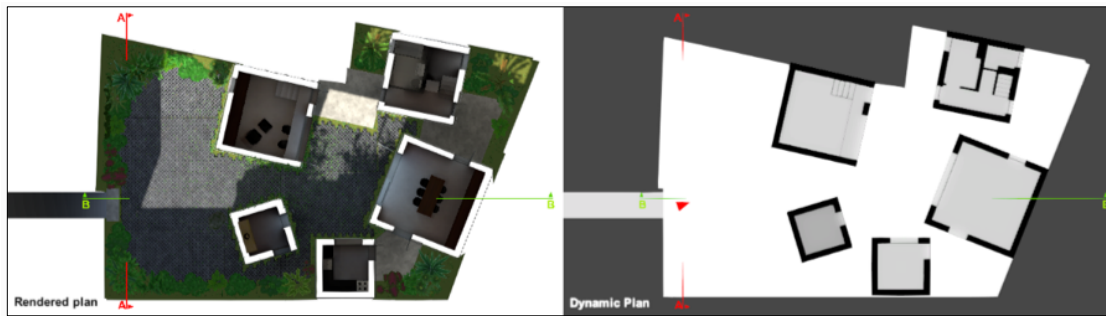


Figure 7.1. Two dynamic plans: one that adheres to the conventions of interior design (left), and another that follows the conventions of architectural drawings (right).

7.2. Interlinking

Kalay (2004), defines *interlinking* as “the ability to link information represented in different ways so that when one representation is modified, the others are too”. This fundamental property of interlinking is presented in the PDR prototype where all external representations, and performances, at different levels of abstraction update based on the selected design option. Furthermore, drawings also update based on the user’s location in the model where the plan, for example, changes as the user moves between different levels. Because the user is represented as an object, viewports that display the user continuously provide feedback of the user's location and local transformations, i.e., rotation, and the journey the user may take in the model. Section drawings, which inherit their location from the user, also update as the user moves around the design option. Additionally, objects may change states based on different criteria. For example, in the axonometric massing model, rooms that are occupied by the user change their representation to express the user’s availability within the boundary of the room. Thus, all representations in the prototype, in one or multiple ways, are interlinked.

7.3. Information Management

According to Kalay (2004), *information management* may be defined as “the ability to organize and access complex information resources”. The PDR prototype in its current state does not allow for the reorganization of information per Kalay's description.

However, it allows for a simulated access to a database where object parameters are accessible. During a design review, access to all that information and the ability of organization and reorganization might not necessarily assist in comprehending the design intent. Nevertheless, some access to object parameters may be needed to comprehend the anomalies that may, for example, occur in a performance-based analysis. Predictability of which information to include in the design review is challenging. The prototype does not allow for the filtering of information per Kalay's description. However, this ability may be considered for future work where the designer can reorganize the interface and all information within at will.

7.4. Visualization

Kalay (2004), defines *visualization* as “the ability to produce photo-realistic images of yet nonexistent artifacts and environments”. Perhaps the above discussion from Kalay on the importance of visualization is one of the primary motivations for the development of this study and creation of the prototype. The prototype adheres to the need and importance of including experiential representation methods in design reviews. In fact, the prime function of the main viewport in the prototype is to provide the ability to dynamically walk-through each design solution. Additionally, extensive effort is spent on the visual quality of the virtual environment. Building elements are not necessarily rendered in their pristine condition. Rather they may include variation in textures and color, some form of decay, and subtle imperfections (Figure 7.2). Objects such as furniture are included to give a sense of scale, and simulated wind is introduced to enhance the realism of trees and vegetation further. In addition to the phenomenological representation of design solutions, one may also walk-through a conceptual, or an analytical representation where every part of the design solution may be subject to scrutiny without the observer losing the sense of scale or spatial awareness.



Figure 7.2. Textures and color variation, decay, and subtle imperfections.

Previous attempts and published work of PDR 2.5 addressed the change in textures (Altabtabai et al., 2016). In PDR 3.0 the focus is on formal change rather than local object changes. Therefore, a deliberate choice was made to exclude material and texture changes, although possible, as these changes have been extensively explored in previous research and publications.

7.5. Intelligence

According to Kalay (2004), *intelligence* can be defined as “the ability to embed design rules, constraints, and goals within the representation itself, making it an active rather than a passive, partner in the design process”. The creation of the prototype requires a multiplicity of design solutions. These design solutions are generated by using a parametric model with embedded intelligence—a set of parameters and constraints. Two parameters for each box are introduced to control the box’s location and rotation. By varying the location and rotation of each box, the algorithm may generate many formally disparate design solutions. Four constraints are embedded in the parametric framework to guarantee the validity of the generated design solutions: *constraint01*

guarantees enough circulation clearance is available between the boxes; *constraint02* tests if a *box* is spatially inside another *box*; *constraint03* tests for the availability of enough clearance between fenestrations, doors and windows, and the property line; *constraint04* guarantees a certain clearance for a specific neighbor's window to grant access to daylight. *Constraints 01-04* determine the validity of the solution

A multi-objective optimization algorithm that facilitates the selection of design options is integrated with the parametric framework. Three criteria and goals are introduced to the optimization algorithm: minimization of solar radiation; maximization of courtyard size; and maximization of privacy for occupants.

While the above process is only a prerequisite for the development of the prototype, a representation of the parameters, rules, constraints, and performances are included in the prototype. The prototype, in other words, can be said to include a set of design options that are based on parameter changes governed by rules and constraints that guarantee the validity of design options.

7.6. Connectivity

Kalay (2004), defines *connectivity* as “the ability to share information rapidly among all the participants in the design process”. Although PDR was made to cater to design studios in academic environments, it may be adaptable to professional practice. The prototype can be shared with different people via an executable file which allows it to run on a different system from the one that was used to develop it. A limitation that may rise from sharing an executable file is due to a major design decision that was made early in the conceptual model of the interface, namely, the need for at least two screens. However, the increased ubiquity of higher resolution displays and high-end graphic cards capable of simultaneously rendering to multiple displays may diminish this limitation over time. Additionally, with the increased speed of computers and internet, it would be possible to carry a design review using the interface in geographically disparate locations and yet use the same representations.

7.7. Summary

To conclude, for Kalay (2004) the mentioned advantages when combined make a qualitative difference in architectural design. For PDR, and reflecting on Kalay's point of view, one may say that PDR allows reviewers and other participants to concentrate on the evaluation of the presented information. At the same time, PDR may help reduce the workload associated with generation and regeneration of representations necessary for design reviews. Because it automatically generates, for example, plans, sections, and elevations, it may reduce errors associated with translation from one form or type of representation to another. Finally, it would allow for better and informed decision making which may be due to the comprehensive set of representations or the thorough communication of embedded intelligence.

8. CONCLUSIONS AND FUTURE WORK

This chapter provides concluding remarks on PDR and future work. This research produced a prototype for a dynamic presentation method of parametric, performance-based, and multi-objective optimal design options for design reviews and then, through focus groups, assessed the prototype in support of a design review. The PDR prototype was achieved by translating an architectural design project into an interactive virtual gaming environment. By using a game engine as a development environment, a novel user interface was designed to simultaneously engage a parametric framework, object parameters, and multi-objective optimized design options and their performances. The prototype couples the developed interface with diagrammatic, perspectival, and orthographic representations in support of a set of functions for design review.

PDR was demonstrated in a series of focus group sessions with faculty members and students at Texas A&M University. Focus group data were used to validate PDR through evaluation of the method's *perceived usefulness* and *theory confirmation* (Davis, 1989; Fern, 2001).

8.1. Contribution to the Body of Knowledge

This research marks the first time where parametric design is presented systematically with a new set of tools that can demonstrate the usefulness of a parametric BIM-based design review method. An extensive literature review has uncovered no other attempt to bring together disparate evaluation and visualization methods of a parametric MOO design options in design reviews. The system integrates a parametric framework, BIM data, quantitative and qualitative assessment methods of multiple optimized design options, and multiple visualization methods to facilitate a comprehensive understanding of a design project. Furthermore, PDR facilitates spatial understanding and consequences of design decisions in real-time. It integrates multiple phenomenological sensitivities such as light, sound, and wind. Analysis of focus group

interviews validated the method and confirmed that PDR is *perceived useful* and that focus group participants would use PDR if the tool was available.

8.2. Summary of Focus Group Results

Data collected from focus group sessions, where PDR was presented, were analyzed to validate PDR. For this study, the main construct is *the perceived usefulness of PDR*. However, sub-constructs that qualify the usefulness of PDR were considered before conducting focus group sessions, while other constructs emerged from analysis of focus group discussions. The following is a summary of each construct followed by focus group analysis results:

The perceived usefulness of PDR, in general: focus group discussion data reveal that in general the ideas demonstrated using PDR are *perceived useful* for both academic and professional practice settings.

Participants' rating of PDR: in general, participants have given PDR high ratings.

Participants' willingness to use PDR: focus group data confirm that faculty members, graduate and undergraduate students, would use PDR if the tool is available.

The perceived usefulness of multiple real-time viewports and automatically generated drawings: focus group discussion data reveal that in general the ability to have multiple viewports to display different information is perceived useful.

The perceived usefulness of integrating performance-based analysis: focus group discussion data reveal that the inclusion of performance-based analysis is perceived useful.

The perceived usefulness of the inclusion of multiple design options: focus group discussion data reveal that, with some reservations, the inclusion of design options is perceived useful.

The perceived usefulness of animated design option morphology: focus group discussion data reveal that the use of animation technique to communicate design option morphology is *perceived useful*.

The perceived usefulness of real-time section drawings: Focus group discussion data reveal that the idea of real-time generated section drawings is perceived useful.

Although the idea of real-time generated drawings in general is perceived useful, the real-time section drawings are *perceived* as being particularly *useful*.

The perceived usefulness of utilizing different visualization methods: focus group discussion data reveal that the use of different visualization communication methods, conceptual, phenomenological, and analytical is perceived useful.

The problem of perceived information overload: focus group discussion data reveal that PDR, as it was presented in the discussion, may have suffered from information overload.

The potential of PDR as a replacement for paper-based design reviews: focus group discussion data reveal that PDR may have the potential to replace paper-based design reviews.

The potential of PDR as a design tool: focus group discussion data reveal that PDR might have the potential to be used as a design tool although it was conceived as design review tool.

The potential of PDR outside of academic settings: focus group discussion data reveal that in general the ideas demonstrated using PDR are perceived useful beyond academic settings.

The importance of perceived ease of use for potential users: focus group discussion data reveal that the *ease of use* is important although no testing for *ease of use* was conducted.

8.3. Future Work

The future development of PDR, as a suggested software tool, may bifurcate into two directions. On the one hand, PDR can be developed into a standalone software where BIM models, including geometric and non-geometric data, may be imported. On the other hand, PDR may be integrated into existing BIM software. Each of these directions necessitates a thorough user study not only to evaluate users' preferences, but also to begin to answer important questions such as: how/what is the best approach for design oriented users, e.g., architecture instructors and students, to interact with PDR?

Furthermore, as explained in *Chapters 4 and 5*, the process of arriving at the final PDR necessitates many complex steps. The diversity and technical expertise required for each step make the process prone to human error. Furthermore, architecture design students are not necessarily expected to develop a deep understanding of such computational methods. Therefore, it stands to reason that the natural continuation of this research may be the automation of the steps explained in *Chapters 4 and 5*. That is the automation of tedious steps required to go from a parametric-BIM model to MOO, design options selection, further environmental analysis, processing of geometric and non-geometric data, and finally to PDR. The automation of the process may reduce the workload of the designer to the following controlled and concise steps: (a) specifying parameters and constraints to generate design solutions; (b) from amongst a list of predefined criteria, specifying criteria and goals to conduct MOO; (c) selection of design options from amongst Pareto front design solutions; (d) from amongst a list of predefined analyses, specifying further required analysis, such as daylighting or energy analysis, to be conducted for selected optimized design options; (e) sending all necessary data to PDR without relying on DCC software.

Moreover, specific enhancements to PDR were suggested by focus group participants. These suggestions in some instances may be interpreted as *research limitations* or, in some cases, as possible investigation themes for future work. The following items were identified as potential improvements that may further enhance the PDR method:

1. Participants in every focus group session have commented on the excessive number of support viewports on Display02. Multiple participants suggested that it would have been useful to be able to minimize, maximize, or hide support viewports during the design review.
2. PDR is developed with the HFT test case in mind. Therefore, features such as animated design option morphology are chosen due to the applicability of such techniques to the scale and formal organization of the HFT. While some participants appreciated the specificity of PDR in relation to the HFT, at the same

time they hoped for additional examples that demonstrate generalized approaches to communicate design, and design option morphology, for different building typologies and at various scales.

3. Many focus group participants hoped for an integrated environment where PDR may be embedded within a design software tool, e.g., Revit or Rhino, or a live link that connects PDR to an existing design software tool. This ability was suggested due to the perceived usefulness of PDR as a design tool in addition to being a design review tool. It also was considered a convenient solution where a live connection between design software and PDR will instantaneously allow for personal design evaluation before committing to design options for design reviews.
4. Focus group participants suggested the extendibility of PDR to include VR or augmented reality (AR) visualization methods. An interesting suggestion had been the inclusion of artificial intelligence (AI) as an active evaluator of design projects. The inclusion of AI is not meant for the evaluation of quantitative performances as that is introduced in the prototype via Pareto Optimality. Rather the suggestion of using AI is meant to qualitatively evaluate a given design option.
5. A focus group participant felt that the inclusion of scale figures in the *navigation evaluation mode* may aid in comprehending the scale of a given design project. PDR currently relies on first-person point of view, furniture, texture, vegetation, and fenestrations to communicate scale. However, when using the *conceptual visualization method*, with the exception of the first-person point of view, all elements that may imply scale specificity, are hidden. Thus, a suggestion was made to include scale figures in the virtual environment to aid in comprehending the scale of the given project.
6. PDR provides complete navigational freedom to the user while in the *navigation evaluation mode*. A participant suggested that the inclusion of suggested routes may aid in better navigation of design options, especially for large-scale projects.

7. Participants suggested that while the *dashboard evaluation mode* was useful, it lacked a comparative or a rating method. A *comparative method* could facilitate the comparison of two or more design options and their performances side by side. A rating score system was also recommended so that the *dashboard evaluation mode* does not rely on numerical feedback of metric but rather a score system. By using a score system, participants suggested that it may be easier to compare and therefore comprehend the performance of design options. Furthermore, a scoring system may make it easier to communicate performances to lay persons.
8. A suggestion was made to include the ability to take snapshots during the design review. The idea is that once a certain viewport, main or support, is considered useful during the design review, the user may take a snapshot of the viewport. This snapshot can then be included as yet another support viewport. For example, if during the design review a certain section cut becomes important for the discussion, the user may take a snapshot of the section and include it as a separate non-dynamic viewport.
9. Some design studios require that students explain the design process and how the formal qualities of the building were developed. Therefore, participants suggested that it would be useful if PDR supported the ability to communicate design process. When the moderator suggested the use of animation techniques such as ones used to convey design option morphology, many participants showed enthusiasm towards the idea.
10. As a solution to the problem of information overload caused mainly by the nine support viewports on Display02, one participant suggested the use of a hybrid technique to arrive at an orchestrated immersive walk-through slideshow. The idea is that PDR would have the ability to display support viewports sequentially and based on the designer's narrative.
11. Live support viewports section cuts A and B were labeled on the floor plan viewports. However, the experimental user-point-of-view section cut was not.

Although students were able to comprehend how it works, some felt that it may be necessary to include the label on the plan to avoid confusion.

12. The feature of different visualization communication methods/styles is implied in PDR via the three visualization methods (conceptual, phenomenological, and analytical). Nevertheless, the comment brought up by students imply that there is a need for diverse visualization styles that may accommodate to different artistic expression and design philosophy.
13. A deliberate effort was made to simulate all the subtle imperfections and minor decay observed in the HFT test case used to demonstrate PDR. However, participants wondered if more severe weathering may be included as an inquiry into the future of the design project/option. Other participants discussed the possibility of occupant space intervention citing the problematics of pristine renderings used for marketing that usually do not resemble the realities of living in a space.
14. A focus group participant suggested the inclusion of a live clipping plane in the navigation evaluation mode. This functionality was indeed planned for PDR but was not included in the presented prototype. The idea is that the user would have a live clipping plane that may be manipulated during the walk-through, and the results of this manipulation will be evident in the main viewport.
15. Students express that layering transparent information on top of the *phenomenological visualization methods* may be helpful. By layering information or simply adjusting the transparency of the *analytical visualization method* on top of the *phenomenological visualization method* users will be able to spatially comprehend the layered information and/or analysis. Furthermore, it was implied that layering the information may cause less cognitive burden than the instantaneous switching between the two visualization methods. Alternatively, another student suggested the decoupling of the different *visualization methods* from *Display01* to other displays for simultaneous *navigation evaluation mode* of the three *visualization methods*.

16. When students were asked if they would like to have a large number of displays when using the interface, the answer was a unanimous “Yes.” One student referenced the BIM-CAVE.

The development of PDR marks a step towards an integrated design review method that may change the current assessment modus operandi of architectural design projects. Ultimately, such a method could improve architectural education and professional practice, leading to improved economic and social environment for the public. This research confirms that PDR is a method that is perceived useful by design instructors, graduate students, and undergraduate students.

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