A Framework for Simultaneously Addressing Qualitative and Quantitative Decision-making Criteria during the Early Stages of the Design Process

Seyedreza Fateminasab

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
In
Architecture and Design Research

James R. Jones, Chair
Steve Harrison
Robert Schubert
Edward Becker

March 3, 2021
Blacksburg, VA

Keywords: Architectural Design Framework, Qualitative and Quantitative Criteria, Design Process, Digital Tools

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ABSTRACT

This study proposes a framework for simultaneously addressing qualitative and quantitative decision-making criteria during the early stages of the design process. It investigates the features and characteristics in an architectural tool that enable an architect to simultaneously address qualitative and quantitative criteria during the early stages of the design process and the requirements for implementing these features and characteristics inside a tool/working environment. It adopts a four-step methodology based on the qualitative methods of inquiry. These steps include logical argumentation based on the literature review, interviews, immersive case study, and Delphi method.

The proposed framework provides a map of the areas and the themes that need consideration when developing an architectural tool that is expected to simultaneously address qualitative and quantitative criteria at the early stages of the design process. It categorizes the themes in three main areas: the themes concerned with qualitative studies, the themes concerned with quantitative studies, and the themes concerned with bridging the gap between qualitative and quantitative studies. The framework suggests that four major themes need consideration while developing architectural tools to support simultaneously addressing qualitative and quantitative criteria: *Imagination Stimulation* for qualitative studies, *Knowledge Acquisition* for quantitative studies, *Architect as Toolmaker and Design Environment Coordinator*, *Hybrid Environment*, and *Interface* for the synthesis of qualitative and quantitative studies. For practicing architects, the framework provides guidance to choose proper tools and form their design environment. Moreover, this study provides a new model of communication between the architecture community and the software developers.

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GENERAL AUDIENCE ABSTRACT

Any architectural project consists of numerous decisions that the architect must make. These decisions have different characteristics and can be categorized in many ways. One way to categorize them could be based on the nature of the criteria that the architects use to evaluate the results of their decision. In this manner, these criteria can be either qualitative or quantitative. Addressing these two different kinds of criteria demands entirely distinctive sets of skills. Architects are trained to address these two fundamentally different kinds of criteria, consciously or not. However, the reasoning process is much more complicated when the decision demands addressing qualitative and quantitative criteria, simultaneously. There exists the possibility that one criterion or one set of criteria may overshadow the rest if this complex task is approached without conscious planning by the architect.

This study proposes a framework for simultaneously addressing qualitative and quantitative decision-making criteria during the early stages of the design process. It provides a map of the areas and the themes that need consideration when developing an architectural tool that is expected to simultaneously address qualitative and quantitative criteria at the early stages of the design process and uses several graphical representations to categorizes these themes based on the needs and objectives of the user.

Dedication

To my parents Zari and Majid

Acknowledgments

This endeavor would not have been possible without the help and support of many people. Although an exhaustive list would be impossible, not trying would be unfair.

Firstly, I like to thank my family Zari, Majid, Ali, and Ghazal. I am aware of the tremendous privilege of having your unconditional love and support. My main motivation to finish my PhD was to be able to come back home and be with you.

I like to thank my advisor, Dr. Jim Jones. My time at Virginia Tech would not have been such a joyous experience without your help and support. I have learned a lot from you, much beyond the scope of this research. But one thing that I cherish most and hope to be able to replicate is your kindness and compassion toward all your students.

I like to thank my committee members. Your kind comments and feedbacks throughout the process encouraged me to move forward and dig deeper.

I also like to thank all the participants in my research. This would not have been possible without you selflessly dedicating your time and expertise.

I like to thank all my friends at Blacksburg. I am lucky that the list is so long that it is impossible to fit it here. Thank you for all the talks, parties, potlucks, hikes, bonfires, trips, film nights, and Cellar hangouts.

Lastly, I like to thank Neda. I was not able to start or finish this without you. You always bring out the best in me. I love you.

Contents

1. Introduction

1.1. Introduction

Any architectural project consists of numerous decisions that the architect must make. These decisions have different characteristics and can be categorized in many ways. One way to categorize them could be based on the nature of the criteria that the architects use to evaluate the results of their decision. In this manner, these criteria can be either qualitative or quantitative. Addressing these two different kinds of criteria demands entirely distinctive sets of skills. Architects are trained to address these two fundamentally different kinds of criteria, consciously or not. However, the reasoning process is much more complicated when the decision demands addressing qualitative and quantitative criteria, simultaneously.

For instance, in designing a window, there are several criteria, both qualitative and quantitative, which affect the final design. The amount of energy transferred through the window or the intensity of daylight provided by it at different times of day or year are examples of quantitative criteria. On the other hand, there are qualitative criteria such as the view or the quality of daylight at various times of day or year. Designing a window that addresses all these criteria is a complex task. Moreover, addressing these criteria simultaneously, requires adequate weighting of each criterion, next to the others. There exists the possibility that one criterion or one set of criteria may overshadow the rest if this complex task is approached without conscious planning by the architect.

Architects have different approaches in addressing this matter. Some try to overcome this task with a more intuitive approach, such as representing numeric values of quantitative criteria graphically in a digital model of the design (Figure 1-1), while others try to convert qualitative criteria to quantitative representation (Figure 1-2). These approaches have both advantages and disadvantages. For instance, in (Fontenelle & Bastos, 2014), reducing the view to the mere sum of sight angles is questionable, even though it gives the possibility of applying quantitative multi-criteria analysis methods.

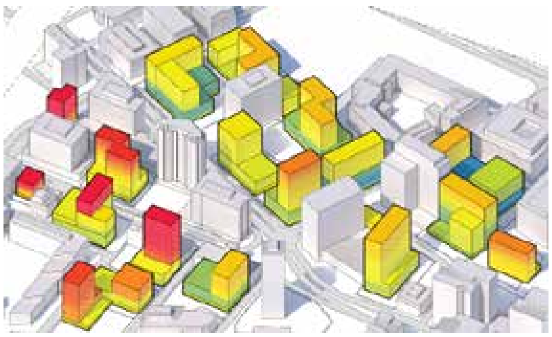


Figure 1-1 Studying daylighting potentials at Kendal Square (MIT Urban Modeling Seminar) by James Perakis and Josh Westerhold. Retrieved October 30, 2016, from http://www.timurdogan.de/

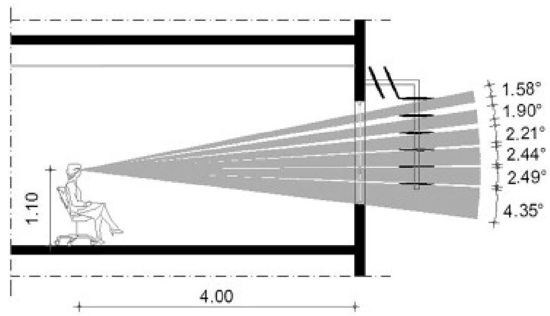


Figure 1-2 Visual angles measured as an indication of view in designing windows for an office building in Rio de Janeiro. (Fontenelle & Bastos, 2014, p. 100)

As seen in the example of designing a window, above, the architects' approach toward addressing qualitative and quantitative criteria during the design process is inherently influenced by their choice of tools. Each tool, whether digital, such as specific software or manual, such as hand sketching, has features and characteristics which either supports or limits employing a specific approach.

Moreover, Thomas Kuhn in his renowned book *The Structure of Scientific Revolutions* (1970, p. 189), argues that tools used by scientists (he provides the example of scientific formulas such as f=ma) signal the "gestalt in which the situation is to be seen." He is arguing that the tools which we use, structure the answers we achieve. Although he is not talking about the field of architecture, his argument is central to an ongoing debate in this field.

During the past few decades, architects have increasingly relied on digital tools. The first wave of these digital tools targeted the final visualization and presentation of the design, in other words, the last stages of the design process. These computer-aided design (CAD) software were generally drafting tools, facilitating the time-consuming and laborious process of hand drafting. However, newer digital tools, such as three-dimensional CAD environments or scripting environments such as Grasshopper or Processing, expand their presence to the very early stages of the design process.

Even though many architects are fascinated with the new possibilities that these digital tools provide, there is a pessimistic feeling about their influence on the design process and its outcome, the design. For example, Juhani Pallasmaa in his book *The eyes of the skin* which discusses the multi-sensory n

1.2. Problem Statement

The focus of this research is on proposing a decision support framework for designing apertures in the building envelope which simultaneously addresses qualitative and quantitative criteria during the early stages of the design process. Both, the best configuration of the available tools and the description of the ideal working environment, that enables architects to simultaneously address these criteria are explored.

Inevitably, to propose an ideal working environment or a new configuration of the available tools, I need to investigate the role of knowledge in developing new tools or internalizing and using those that exist. It is essential to have a clear vision about the kind, the boundaries, and the depth of knowledge that is necessary to effectively utilize a specific tool during the design process.

In this research, I am mostly concerned with the early stages of the design process, since during these stages of design, architects can more easily shift between different design alternatives and their decisions have a more substantial influence on the final design. A well-known diagram (Figure 1-3), best known as MacLeamy effort curve (HOK Network, 2010) (although it can be traced back to (Paulson Jr, 1976) represented here as Figure 1-4), illustrates this fact, arguing the earlier a decision is made, it requires a lower level of effort (cost) while having a higher level of influence.

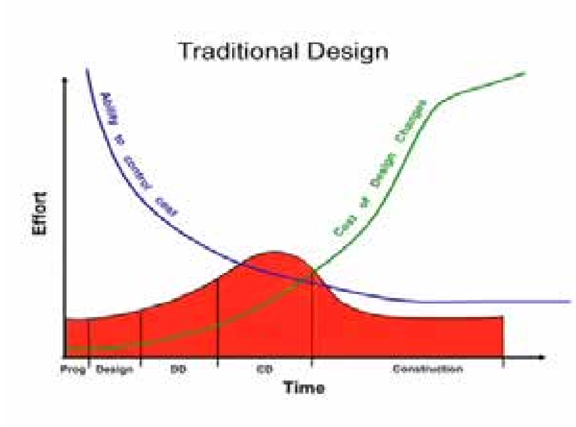


Figure 1-3 MacLeamy effort curve (HOK Network, 2010)

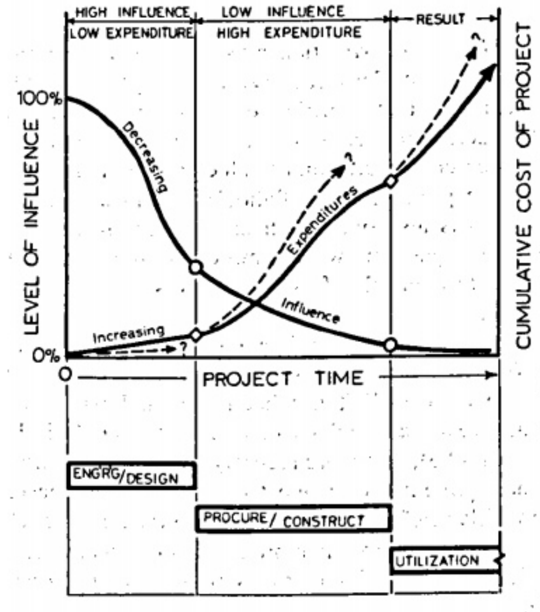


Figure 1-4 Paulson cost/influence curve (Paulson Jr, 1976)

It needs to be stated that I am not trying to propose modifications to the design process. On the contrary, I am trying to propose modifications to the tools that architects use, and the way they use them, with the objective of enhancing the harmony between the tools and the design process. I am trying to eliminate the possible hiccups that can be caused by the tools which architects use during the design process. Of course, all these objectives are delimitated within the boundaries of the scope of this research, which simultaneously addresses qualitative and quantitative criteria.

To summarize, my research questions are:

> What are the features and characteristics in an architectural tool, which enable an architect to simultaneously address qualitative and quantitative criteria during the early stages of the design process?
>
> How can these features and characteristics be implemented inside a tool/working environment?

1.3. Research Methodology

To approach this problem, I go through four steps. Each step is intended to bring new insights and shape and revise the proposed framework. These steps include logical argumentation, interviews, immersive case study, and the Delphi method. These multiple steps are intended to triangulate the research design. The research design generally relies on qualitative methods of inquiry. For details regarding the methodology, please refer to Chapter 3 Methodology.

1.4. Research Philosophy

As qualitative research, it is important to establish the philosophical standpoint of this research at the start, since many aspects of the research, including its methodology, are deeply influenced by it.

This is exploratory research that investigates the features and characteristics of a working environment that would enable architects to simultaneously address qualitative and quantitative criteria during the early stages of the design process. In this regard, since it does not make prior assumptions or a hypothesis about these features and characteristics, it falls under the definition of grounded theory. Instead, these features and characteristics are intended to emerge from the research data. (Please refer to section Grounded Theory)

Moreover, this research should be viewed through its corresponding paradigm and theoretical framework. The research has fundamental assumptions about the role of the researcher, the nature of the knowledge, etc. which are only justifiable when there is a clear understanding of the research and the researcher's paradigm and theoretical framework. This research has ontological and epistemological assumptions that categorize it under the general definition of constructivism as a research paradigm. David Wang and Linda Groat (2013, p. 79) provide this general definition: “constructivism adopts a subjectivist epistemology whereby knowledge

being studied.”

On another level, this research relies on phenomenology as its overarching theoretical framework. Groat and Wang (2013, p. 95) argue that: “phenomenology emphasizes the holistic depth of the participant’s or author’s experiences; from them, generalizations are made about the essence of such experiences.” Using Seamon’s (2000) three categories of phenomenological research in the field of architecture, the methodology for the current research would be identified as a middle ground between first-person and existential phenomenological research. Seamon describes the first-person approach as: “the researcher uses her own firsthand experience of the phenomenon as a basis for examining its specific characteristics and qualities”. While his definition of existential approach is: “the specific experiences of specific individuals and groups involved in actual situations and places.” (Please refer to section Phenomenology for more details)

1.5. Research Contributions

The results of this research help to make the process of adopting an approach toward the problem of simultaneously addressing qualitative and quantitative criteria during the early stages of the design process, more conscious. A conscious approach eliminates the possibility of ignoring one set of criteria in favor of the other. The proposed decision support framework for designing apertures in the building envelope helps architects to simultaneously address criteria such as sustainability and placemaking through the simultaneous qualitative and quantitative studies such as view and glare during the early stages of the design process. This leads to more comprehensive decisions by different parties involved in an architectural design project, thus producing more responsive designs.

Also, it is beneficial from a pedagogical point of view. It acquaints architecture students with different approaches to this matter and helps them to consciously choose, practice, and utilize these different approaches in diverse situations. Moreover, adopting the proposed decision support framework makes architects more vigilant about simultaneously addressing both qualitative and quantitative criteria in the process of design, which will lead to the development of more complex models for doing so.

But most fundamentally, the objective of this research is to put forward a new communication model between the architecture community and the software developers. It challenges the current power dynamics and proposes a more active role for architects in this partnership.

2. Literature Review

2.1. Introduction

Umberto Eco in his book *How to write a thesis* (2015) provides a simple, straightforward description of literature review: “In a literature review, the student simply demonstrates that he has critically read the majority of the existing ‘critical literature,’ or the published writings on a particular topic.” (2015, p. 3) He provides further details pointing out that “The student explains the literature clearly, connects the various points of view of its authors, and thus offers an intelligent review, perhaps useful even to a specialist in the field who had never conducted an in-depth study on that specific topic.” (2015, p. 3)

Groat and Wang describe the difference between literature reviews and annotated bibliographies by pointing out that “Annotated bibliographies demonstrate knowledge of the general literature relevant for the researcher’s area of interest. In contrast, literature reviews synthesize themes within that literature.” (2013, p. 142) They provide further detail about the literature review by pointing out that “These syntheses entail assessment and critique of existing perspectives, but also offer new ideas. From these ideas emerge original research questions.” (2013, p. 142)

In this chapter, I will start with the design process and different models that are proposed for representing it. After that, I will investigate a brief history of digital tools in architectural design. The history of computer-aided design (CAD), alone, can extent to a lengthy PhD dissertation for itself. To avoid this, I will only address parts that have direct relevance to my research topic. For the rest, I will only hint at other resources. In the next section, I will address the distinction between the act of architectural design and visualization. Next, I will investigate previous researches that have a strong theme of simultaneously addressing qualitative and quantitative criteria during the design process. After that, I will focus on specific areas that I tackle in my research questions; the first area is a pedagogical exploration of knowledge for applying a digital tool in the field of architecture, and the second area is the concept of visual comfort and the problem of glare in architectural spaces as a good example of where qualitative and quantitative decision-making becomes critical.

2.2. Design Process

Any working environment which architects use, at any stage of the design, and their reasons for their choice, is intertwined with their understanding of the design process. Therefore, it is important to establish the context of this research toward the design process at the beginning.

It is difficult to describe the characteristics of the design process, without first addressing the characteristics of the design problems and the proposed solutions, or the design as a noun. Cross (2006, p. 7) argues that the main characteristic of design solutions is that they are quick satisfactory ones, rather than optimized solutions which are analyzed in detail. Lawson (2006) describes this characteristic from another perspective, arguing that architects have a solution-focused strategy, in contrast to scientists who have a problem-focused one. He comments: “The essential difference between these two strategies is that while the scientists focused their attention on understanding the underlying rules, the architects were obsessed with achieving the desired result.”

Cross (2006, p. 7) also mentions this widely accepted assumption that design problems are ill-defined and ill-structured. This means that these problems, in contrast to scientific problems, are inherently incomplete, and need further construction by the designer. It is due to this characteristic which Cross argues that designers need to "define, redefine and change the problem-as-given in the light of the solution that emerges from their minds and hands" (2006, p. 7) Or as Akin (1979) puts it: "One of the unique aspects of design behavior is the constant generation of new task goals and redefinition of task constraints."

Cross (2006, p. 16) talks about a three steps iterative modeling, testing, and modifying process as the central activity of the design process. He also mentions a reciprocating characteristic in the design process: "although there is a hierarchical structure of decisions, from overall concept to details, designing is not a strictly hierarchical process; in the early stages of design, the designer moves freely between different levels of detail." (2006, p. 37) He also argues that the tools which designers use (here sketching) facilitate this: "sketches enable designers to handle different levels of abstraction simultaneously." (2006, p. 37)

Another interesting study, (Gunther et al., 1996), divides the design process into three major stages (clarifying the task, searching for concepts, and fixing the concept) and measures the time spent at each step in an experimental group design project (Figure 2-1). Here too, the reciprocating characteristic of the design process is presented, as even until the end of the project, the designers are moving between these three stages of the design process.

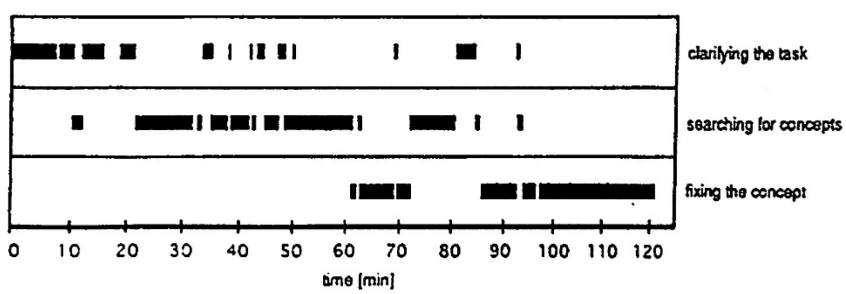


Figure 2-1 Time spent at each stage of the design process (Gunther, Frankenberger, & Auer, 1996)

Lawson (2006) too, names three iterative design process activities; analysis, synthesis, and evaluation (Figure 2-2). Commenting about the reciprocating characteristic of the design process, he mentions: “The map, such as it is, no longer suggests any firm route through the whole process. It rather resembles one of those chaotic party games where the players dash from one room of the house to another simply in order to discover where they must go next.”

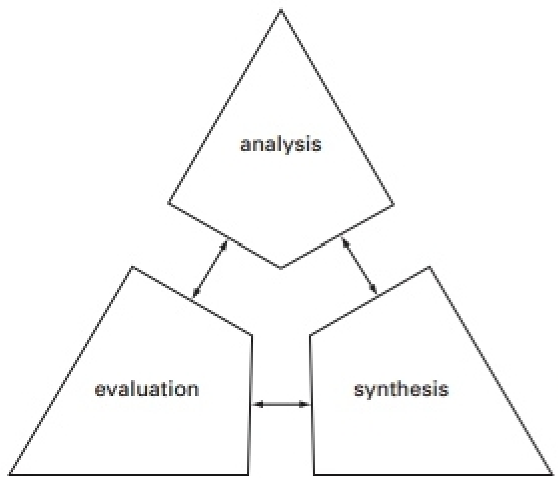


Figure 2-2 Design process (Lawson, 2006)

These previous studies illustrate that although we have a relatively established model for the design process, its reciprocating characteristic is the feature that is often neglected. As mentioned before, Cross (2006, p. 37) argues that sketches, as a tool, facilitate this characteristic, but it seems that most computer software that architects use are lacking this feature. It can be argued that representing this characteristic in a schematic diagram of the design process (Figure 2-3) can encourage the implementation of this feature in other tools that architects use during the design process.

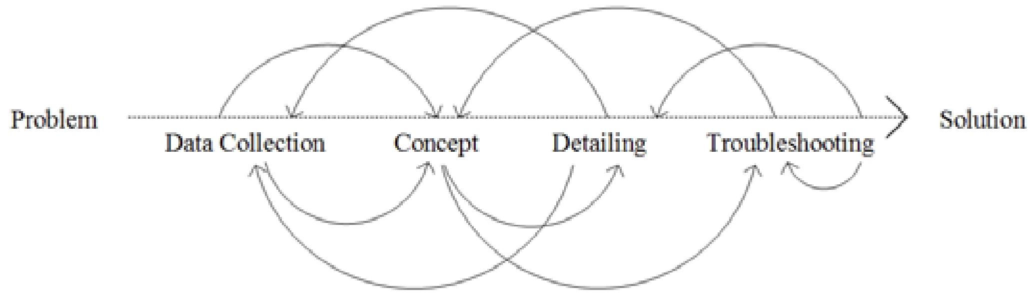


Figure 2-3 A proposed schematic diagram of the design process representing its reciprocating characteristic

This diagram represents the path (the jumps from one area of the spectrum to the other) which the architect goes through. As time passes these jumps become shorter and mostly concentrated toward the right side of the spectrum.

2.3. The History of Digital Tools in Architectural Design

Peddie (2013) in his book *The history of visual magic in computers* provides a detailed history of computer-generated graphics, including the development of the necessary mathematical and geometrical prerequisites, computer hardware, and software. He argues that "Computer-Aided Design (CAD) was the first major application for 3D in computers." (2013, p. 102) Although we usually attribute the D in CAD to design, the first emerging digital tools which were used in the design process were merely drafting tools. (Peddie, 2013, p. 48)

As Thilmany (2007) argues, specifying the start point of CAD, or as some prefer "the father of CAD", is hard. A rational compromise would be to address both Patrick Hanratty (interestingly, representing the efforts made by the industry) and Ivan Sutherland (representing the efforts made by the academia).

Peddie (2013) and also Sathyanarayana & Kumar (2008) and Waurzyniak (2010) refer to Patrick Hanratty as "the father of CAD/CAM" for developing PRONTO, "the first programming language to automate machine tools" (Thilmany, 2007) in 1957 while working at General Electric (GE). This was the first attempt to commercially develop computer numerical control (CNC) machines.

Later, in 1958, General Motors (GM) initiated investigating the use of computers in the design process in its General Motors Research Laboratories (GMR). (Krull, 1994) In 1959, they started a project with the collaboration of IBM, called "digital design", which later changed its name to "Design Augmented by Computers" or DAC-1. (Krull, 1994) DAC-1, which was publicly presented for the first time in 1964, "had advanced functions like transformations on geometric objects for display, rotation, zoom, and clipping." (Peddie, 2013, p. 103) Fred Krull and Patrick Hanratty were "the pioneering GM engineers working on DAC-1." (Peddie, 2013, p. 103)

In academia, it was Sketchpad that brought Ivan Sutherland the title of "the father of CAD" (Tornincasa & Di Monaco, 2010). In 1959, MIT started a project, funded by the United States Air Force, called "Computer-Aided Design Project". (Weisberg, 2008) In 1961, Ivan Sutherland used one of the computers in MIT Lincoln Labs to develop Sketchpad (a.k.a. Robot Draftsman) as part of his PhD thesis. (Peddie, 2013, p. 98) He, later on in 1963, published his thesis, and a paper, describing Sketchpad. (I. E. Sutherland, 1963) The title, "Sketchpad: A Man-Machine Graphical Communication System", shows that he was contemplating about the way the user communicates with the computer.

Sketchpad "had one of the first window-drawing program and clipping algorithm, which allowed zooming." (Peddie, 2013, p. 99) In a video of a lecture given by Ivan Sutherland (1994), describing Sketchpad, other features such as snapping and "rubber band" lines are mentioned, which continue to exist in today's CAD software. Peddie describes Sketchpad as "innovative, and influenced the interaction with computers", pointing out that "a user could draw horizontal and vertical lines and combine them into figures and shapes. It could accept constraints and specified relationships among segments and arcs, including the diameter of arcs. It had the ability to copy figures, move them, rotate, or resize them while retaining their basic properties." (2013, p. 99) Both Sketchpad and DAC-1 used "light pen" as an input device to draw and interact with a cathode ray tube (CRT) display.

During the 1960s, many companies started developing CAD systems. At that time, as Peddie explains, "computer companies did not differentiate between hardware and software as they do today, they developed both." (2013, p. 104) Weisberg (2008) provides a detailed history of many of these companies in his online-published book *The Engineering Design Revolution: The People, Companies and Computer Systems That Changed Forever the Practice of Engineering*. Few of these companies are still active today, most of them were acquired by other companies.

The biggest player in today's CAD market, Autodesk, was founded in 1982 by John Walker with 17 partners. (Peddie, 2013, p. 105) The company's famous product, AutoCAD, was based on "a CAD program written in 1981 by Mike Riddle which was initially called Interact and subsequently MicroCAD before taking on the AutoCAD name." (Peddie, 2013, p. 105) As Peddie puts it: "The program, designed to run on the new low-cost PCs, revolutionized the industry and swept the rug out from under many of the big CAD companies." (2013, p. 105)

Weisberg mentions that in 1977, when Riddle was working on Interact, "At the same time, he was working as a consultant for the Frank Lloyd Wright Foundation in Scottsdale, Arizona developing an accounting system for the foundation. … This provided him an opportunity to observe their design process, and Interact began to be used for some actual architectural work." (Weisberg, 2008, p. 1 Chapter 8)

Weisberg argues that one of the important development leaps for AutoCAD has been the implementation of the add-on system through AutoLISP in 1985, which enabled third-party programmers to develop and add additional, specialized features to AutoCAD. (2008, p. 9 Chapter 8) John Walker, one of the founders and the long-term CEO of Autodesk, in his online-published book *The Autodesk File Bits of History, Words of Experience* provides a further detailed history of the company. Walker's argument for choosing LISP programming language, interestingly, opens a door to his view of AutoCAD as a design product: "Unlike programming languages such as C and FORTRAN, which force one to organize a problem entirely before programming, Lisp encourages exploring various approaches to a problem interactively, exactly as CAD helps a designer." (1994, p. 251)

Weisberg's argument resonances with Davis & Peters (2013) argument in their paper titled *Design Ecosystems: Customising the Architectural Design Environment with Software Plug-ins.* They argue that even though scripting inside CAD environments, enabling the user to add a specific feature, has been possible for decades (in the case of AutoCAD as we discussed, from 1985) its real potentials and possibilities are only becoming evident after the emergence of Grasshopper (a graphical programming environment that runs within Robert McNeel & Associates' Rhinoceros CAD software) developed by David Rutten.

They, borrowing their analogy from Eric Raymond, attribute Grasshopper's design environment to a bazaar ("a marketplace in which the collective action of individuals contributes to the larger community") compared to traditional self-sustained CAD environments, which they attribute to a Cathedral. They argue that this new add-on-based design environment puts the designer in the role of the coordinator and creator of the design environment itself. An environment which is “continually changing in dialogue not only with the project but also with particular stages of it.” (2013, p. 131)

Davis & Peters also argue that “The role of the architect as the creator of generative scripts or developer of plug-ins goes beyond the creation of conventional digital 3-D models. It also goes beyond that of toolmaker, as creation, modification and coordination of the design environment becomes an integrated part of the design product.” (2013, p. 131)

This enthusiastic argument justifies a deeper look at the history of Robert McNeel & Associates company and their famous CAD product Rhino. McNeel & Associates was founded in 1980 by Robert McNeel, “developing accounting software for consulting firms”, which corresponds with Robert McNeel’s background in public accounting. By 1985, the company starts developing AutoCAD based products, such as AccuRender. In 1992, they start developing Rhino, also as an AutoCAD plug-in, but soon they realize that the “AutoCAD user interface was not adequate for 3 D free-form design”. Therefore, they start to develop Rhino as a standalone Windows application. (Folini, 2007)

The first version of Rhino is released in 1998. In 2006, McNeel & Associates hires David Rutten, a TU Delft architecture graduate. In an interview in 2011, David Rutten mentions that “They [McNeel & Associates] have never been able to tell me exactly what they expected from me, and I have a feeling it was more an experiment in hiring than anything else” (Tedeschi, 2011) Rutten ends up developing grasshopper, a graphical algorithm editor plug-in for Rhino, inspired by Bentley’s Generative Components (GC), and released for the first time at 2008. (Tedeschi, 2011)

2.4. The Act of Architectural Design and Visualization

Antoine Picon in the article *Architecture, Science, Technology, and the Virtual Realm* argues that architecture by definition is the production of virtual content. He argues that "etymologically, virtual means full of virtue, virtue being taken here as a capacity to act." So, in his view, virtual reality is a "potential awaiting its full actualization." Or in other words, a reality which "its full development or presence […] is partly lacking." (2003, p. 295) His argument, in some respects, seems rhetoric and a play by words, since although this definition of virtual reality and the concept of virtual reality in the field of information technology are both assigned to one phrase, but they are not necessarily equivalent.

He argues that, by the eighteenth century, architects distanced themselves from Vitruvius's definition of architecture as the art of building and looked at architecture as the production of a mental image or as *Etienne-Louis Boullée* wrote: "That production of the mind, that creation, constitutes architecture." (2003, p. 297) Picon argues that this paradigm shift alters the meaning of architecture from either "a collection of remarkable buildings" or "the aesthetics, utilitarian, and constructive rules that make these buildings remarkable", to the production of a more intellectual and virtual content. He argues that architecture is the principle that enables constant exchange between virtual reality and the built reality.

Going back to the point that an architectural design as virtual reality and the concept of virtual reality in the field of information technology (for example, a 3D model of a building) are not equivalent; the design as virtual reality, or the mental image, is an abstract entity which solely exists in the mind of the architect. The building itself, on the other hand, belongs to the built reality which everyone can perceive through different senses, although each person will have a different perception of it, phenomenologically speaking. Now the 3D model stands somewhere in the middle of this; it is, without doubt, outside the domain of physical reality, but also, it is not an abstract entity, since it can be perceived by everyone through senses, here only the vision.

By extending this argument, the building itself, as a physical entity, and any other architectural visualizations of it, whether virtual as a 3D model or physical as a hand-drawn sketch, are nothing but representations of the abstract entity, which is the architectural design, the mental image. This is the direct consequence of the paradigm shift in the meaning of the architecture that was mentioned in the previous paragraphs. The originality of architecture is now beyond reality, whether built or virtual. And for this reason, imagination becomes the central characteristic of the act of architectural design. Or as Picon too mentions, imagination becomes “man’s ultimate creative faculty” and is given “precedence over other intellectual qualities such as pure reason.” (2003, p. 297)

These arguments play a pivotal role in this research whether trying to come up with a decision support framework for the design process or trying to improve or import new tools to the design process such as immersive environments or digital sketching. It is important to keep in mind that all these are working on a different level than the design itself, which is an abstract entity. These frameworks and tools (even the traditional ones like a hand-drawn sketch) help the architect to bring the abstract, the mental image, into a higher level of virtual reality. And by doing this, by bringing the abstract mental image to a higher level of virtual reality, the design becomes perceivable, both for the architect and others.

However, it should be kept in mind that imagination, as the driving force of the mental image production, belongs to the abstract realm, even though it may get stimulated by the perceivable. So, the role which any entity belonging to the realm of the perceivable, including sketches, models, and frameworks, can play on the mysterious course of imagination, is nothing more than a stimulus. And it is by this acknowledgment, that these tools can play their role to their maximum capacity.

2.5. Qualitative and Quantitative Criteria During the Design Process

The approach which tries to convert qualitative criteria to quantitative ones attempts to reduce the qualitative criteria to measurable aspects. Fontenelle and Bastos (2014), in a study, conducted to design the windows of an office building in Rio de Janeiro, try to find a compromise between view, which is a qualitative criterion, and the amount of daylighting and energy consumption, which are quantitative criteria. The study intends to choose one from a set of six alternative designs, differing in size, type of glass, and solar shading devices. (Fontenelle & Bastos, 2014, p. 96)

To “quantify” the view, they define it as the sum of sight angles. They measure the sight angles for a hypothetical person, sitting on a chair four meters away from the window, looking straight toward it. (Fontenelle & Bastos, 2014, fig. 3) The advantages of such an approach are obvious. By reducing the view of a specific window to a numeric value, such as 20.42º, the authors are able to use mathematical multi-criteria analysis methods and software (here CELECTRE software) to find an optimum solution.

However, reducing the view to a mere sum of sight angles is questionable and extremely simplistic. The method is indifferent to what is seen through the windows and even when it comes to measuring how much is seen through the windows; it uses a static viewpoint which is unrealistic. Therefore, even when the total sight angle of a specific alternative is greater than another one, it does not necessarily mean a better view. This, in turn, raises the phenomenological question of what a better view is, which the study does not cover.

The other approach tries to represent numeric values of quantitative criteria, graphically, in order to able the architect to make an intuitive decision. The study by Coley and Schukat (2002) tries to combine optimization of the thermal performance of the building, which is a quantitative criterion with the aesthetic appeal of the building, which is a qualitative one, during the design process.

The study uses a genetic algorithm that generates a large number of random designs; each design's total energy consumption is calculated with a thermal modeling software, then the designs with the lowest total energy consumption are chosen for the next round of design generation and mutation by the algorithm. When the algorithm reaches the end, a relatively large number of designs are produced which all of them are in a 5% to 10% range from the absolute optimum thermal design. At this point, a visual summary of the most varying designs is presented to the architect to choose from.

The major deficiency of the study's method is in its limited interaction with the architect in the process. The architect only gets involved after the algorithm has made substantial decisions about the final design, such as the orientation of the building, and there is no way for the architect to know what the thermal consequences are of changing or modifying these decisions, which leads to the other significant deficiency of the method.

There is no control over the algorithm to make sure that all the possible design alternatives have been generated and processed by it and we know that this task is impossible. So, at best, the algorithm is only generating the most common and standard-looking designs. Therefore, even if the proposed method encourages architects to explore different possibilities for designing a thermally high-performance building, as the authors argue (Coley & Schukat, 2002, p. 1246), it is significantly restricting their imagination when it comes to other criteria since they cannot modify the algorithm's proposals.

In another study by Andersen et al. (2008), the authors follow the same approach, this time with daylighting as the central quantitative criterion. The authors propose a working interface, Lightsolve, (Figure 2-4) inside which graphical representation of numeric values of the quantitative criterion (daylighting), such as condensed annual performance data (presented as Temporal Maps) or the current daylighting conditions (presented as sky view, surroundings and sun angles on elevations), are displayed right next to the corresponding visual effect (presented as interior renderings).

Figure 2-4 Lightsolve working environment (Andersen et al., 2008, fig. 5)

Although this working interface provides the architect with complete control over the design, an important feature lacking in the previous study, it still suffers from several disadvantages. The most important one is that the working interface remains as a detached analysis environment which interrupts the design process flow. In other words, the architect needs to develop the design to a certain level of detail, to be able to import it into the Lightsolve working interface for analysis. Also, the report produced by the Lightsolve working interface is neither real-time nor in the same working environment that the architect usually works in, so the architect needs to study the report and modify the design in its native working environment and then import it again to the Lightsolve working interface for the second round of analysis and so forth.

These disadvantages lead the authors to propose a hypothetical goal-driven design support expert system. (Andersen et al., 2008, pp. 603–604) The authors imagine an environment that enables them to set several goals, based on the reports provided by Lightsolve, and the expert system proposes several different strategies for achieving each goal. The architect is then able to manipulate the model inside the same environment and run the analysis process again. The authors believe that such an environment would imitate the same "interaction a designer would have with a consultant, making it conducive to a more natural design process". (Andersen et al., 2008, p. 603)

These previous studies illustrate that the approach which tries to represent quantitative criteria, graphically, in order to able the architect to make an intuitive decision is generally more inclined to integrate into the design process successfully, rather than the approach which tries to quantify the qualitative criteria. They also show that the interaction of the architect during the whole process is an inevitable feature. Moreover, they indicate the need for a real-time integrated design environment that provides the architect with the necessary analytical data, in an appropriate graphical manner.

The reviewed literature also indicates a lack of phenomenological analysis of the qualitative criteria in such studies. Although subjects such as view, or the quality of light is examined in these studies, the phenomenological theoretical background of these subjects is never discussed. This overlooked perspective can provide new orientations for modeling an improved real-time integrated design environment.

2.6. Knowledge

Proposing either a new configuration of existing tools or an ideal working environment for architects to simultaneously address qualitative and quantitative criteria during the design process, inherently, raises the question of knowledge. What should an architect know before effectively using a specific tool? What parts of this knowledge are previously covered in a general architecture curriculum and what parts require a distinctive learning process? These questions require this research to address the concept of knowledge in the context of education.

There are different kinds of knowledge involved with the adaptation of a new tool. One of them is *a priori* knowledge. The Stanford Encyclopedia of Philosophy defines *a priori* knowledge as "knowledge based on *a priori* justification." (Russell, 2020) It defines *a priori* justification as "a type of epistemic justification that is, in some sense, independent of experience." (Russell, 2020) As Russell points out:

> "*a priori* justification provides reasons for thinking a proposition is true that comes from merely understanding, or thinking about, that proposition. In contrast, *a posteriori* justification requires more than merely understanding a proposition. Observations based on our senses, or introspection about our current mental state, are needed for us to be empirically, or *a posteriori*, justified in believing that some proposition is true." (2020)

However, in architectural research, the term "*a priori* knowledge" is usually used in a less strict meaning. Peter Rowe in his article, *A Priori Knowledge and Heuristic Reasoning in Architectural Design*, points out that: "the term '*a priori* knowledge' as used in this essay simply means knowledge acquired before tackling a particular design problem." (1982, p. 23)

One should notice that the knowledge necessary to use a tool is not limited to factual or declarative knowledge ("knowledge of facts, concepts, events, and objects" which typically can be "directly expressed as a proposition, image, or relational structure" and consists of information stored in long-term memory (*Declarative Knowledge*, 2012)). It heavily relies on tacit knowledge. Tacit knowledge, or implicit knowledge, is usually defined as knowing how versus knowing what. (Hager, 2012)

Hager points out that "tacit knowledge is, literally, the knowledge that cannot be put into words." This description of tacit knowledge is closely resembling Cross's (2006) representation of the design as a way of knowing. Cross argues that while science and humanities rely on numeracy and literacy, design as the third area of knowledge mostly relies on non-verbal modes of thinking. He mentions that the design process heavily depends on graphic images: "drawings, diagrams, and sketches that are aids to internal thinking as well as aids to communicating ideas and instructions to others." (2006, p. 11)

He also suggests that since design ability fundamentally relies on non-verbal media of thought and communication: "there may even be distinct limits to the amount of verbalizing that we can productively engage in about design ability." (2006, p. 19) This is similar to Daley (1982) conclusion that: "The way designers work may be inexplicable, not for some romantic or mystical reason, but simply because these processes lie outside the bounds of verbal discourse: they are literally indescribable in linguistic terms." Moreover, it is interesting that how Cross compares sketching to a "critical, reflective dialogue" (2006, p. 37); further detailing this general idea.

However, to effectively use a tool, there is a specific kind of tacit knowledge involved, usually referred to as procedural knowledge. It is defined as the "knowledge about how to perform a specific task." (*Procedural Knowledge*, 2012) It is the kind of knowledge that is utilized while riding a bike or driving a car. Procedural knowledge is “conceptualized as a condition-action pair […] that links an initiating cue with appropriate cognitive or psychomotor responses.” (*Procedural Knowledge*, 2012) The development of procedural knowledge is heavily relied on practice as a method to reduce the learner’s dependence on declarative knowledge (which consciously layouts the steps) and to refine the conditional cues. “Extensive practice leads to the development of skill automaticity, in which procedural knowledge is executed without any need for conscious monitoring.” (*Procedural Knowledge*, 2012)

2.7. Visual Comfort and Glare

The International Commission on Illumination (CIE) defines glare as: “condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts” (*Glare | Eilv*, n.d.) As it is mentioned in this general definition, glare is often categorized based on its effect on the observer. In this regard, one category is disability glare, which impairs vision without necessarily causing discomfort. The other one is discomfort glare, which produces discomfort without necessarily impairing the vision.

Moreover, glare can be categorized, based on its source, into two groups. One group, referred to as direct glare, is the “glare resulting from high luminances or insufficiently shielded light sources in the field of view.” (*Direct Glare | IES*, 2017) The other group, reflected glare, is the “glare resulting from reflections of high luminance in polished or glossy surfaces in the field of view.” (*Reflected Glare | IES*, 2017)

It should be mentioned that other factors, including psychological ones, influence the perception of glare too. For instance, (Kent et al., 2015) argue that “glare sensation varies with the time of day." They conclude that as the day progresses, people show greater tolerance to luminance in an artificial lighting situation. Another study, (Wolska & Sawicki, 2014), illustrates that younger participants (35 years old or less) are more sensitive to discomfort glare, compared to older participants (aged 50 years and more).

The most interesting psychological factor influencing the glare, and the closest one to this research, is the view. Tuaycharoen and Tregenza (2007) investigated the relationship between the view through a window and the level of discomfort glare. They conclude that "There is less discomfort glare from a window with an interesting view than from either a neutral screen or a window with a poor view having the same daylight glare index."

There are various metrics designed to qualitatively predict glare in different conditions. Several studies compare these metrics and try to provide insights for choosing one over the others. For example, Jakubiec and Reinhart compare "simulation results for five glare metrics under 144 clear sky conditions in three spaces in order to investigate the ability of these metrics to predict the occurrence of discomfort glare." (2012, p. 149) The metrics are Daylight Glare Index (DGI), CIE Glare Index (CGI), Visual Comfort Probability (VCP), Unified Glare Rating (UGR) and Daylight Glare Probability (DGP). They point out that "Discomfort glare is an underutilized parameter in contemporary architectural design due to uncertainties about the meaning of existing metrics, how they should be applied and what the benefits of such analysis are." (2012, p. 149) They conclude that "Daylight Glare Probability yields the most plausible results." (2012, p. 149)

Their finding is similar to Wienold and Christoffersen (2006) claims about their proposed metric, DGP. They argue that "The DGP showed a very strong correlation (squared correlation factor of 0.94) with the user's response regarding glare perception." (2006, p. 743) They point out that “DGP is a function of the vertical eye illuminance as well as on the glare source luminance, its solid angle and its position index.” (2006, p. 743)

For architects, choosing a metric is to some degree influenced by their choice of software too. For example, DIVA for Rhino uses the DGP metric for glare analysis. (*Point-in-Time Glare*, n.d.) Although, EVALGLARE, a more low-level tool, uses DGP by default but is able to use other metrics as well. (Wienold, 2016)

2.8. The Initial Framework

Several themes emerged during the literature review through logical argumentation. (refer to 3.3.1 Logical Argument) These themes were further developed, and their thematic relations were investigated during the interview step. (refer to chapter 4) The following list provides an overview of these themes in alphabetical order:

A priori knowledge: The Stanford Encyclopedia of Philosophy defines *a priori* knowledge as “knowledge based on *a priori* justification.” (Russell, 2020) It defines *a priori* justification as “a type of epistemic justification that is, in some sense, independent of experience.” (Russell, 2020) Peter Rowe in his article, *A Priori Knowledge and Heuristic Reasoning in Architectural Design,* points out that: “the term ‘*a priori* knowledge’ as used in this essay simply means knowledge acquired before tackling a particular design problem.” (1982, p. 23)

Architect as toolmaker and design environment coordinator: This theme was developed through discussion of Davis & Peters (2013) article. They argue in favor of the new add-on-based design environment made possible by the introduction of

Grasshopper which puts the designer in the role of the coordinator and creator of the design environment itself.

Architect's control: This theme emerged as a critique of the Coley and Schukat (2002) study in section 2.5 Qualitative and Quantitative Criteria During the Design Process. As mentioned there, the major deficiency of the study's method is in its limited interaction with the architect in the process.

Architecture community involvement: Weisberg mentions that: "[working at Frank Lloyd Wright Foundation] provided [Mike Riddle] an opportunity to observe their design process, and Interact [the initial version of AutoCAD] began to be used for some actual architectural work." (2008, p. 1 Chapter 8)

Dialogue: Cross discusses the crucial role of reflective dialogue through sketching during the design process. (2006, p. 37) He argues that: "acknowledging the dialogue or 'conversation' that goes on between internal [mental processes] and external representations is part of the recognition that design is reflective." (2006, p. 33) From another point of view, Williams and Tsien argue that one benefit of a sketchbook (consisting of all the hand sketches done for a project by various people in the design team) is its ability to facilitate a simultaneous process of collective ideation: "There are several reasons why the sketchbook is useful. It allows several people to work on parts of a specific section at the same time." (1999)

Evolving: This theme was developed through discussion of Davis & Peters (2013) article. They argue in favor of the new add-on-based design environment made possible by the introduction of Grasshopper which is "continually changing in dialogue not only with the project but also with particular stages of it.” (2013, p. 131)

Hybrid environment: This theme was developed through discussion of Davis & Peters (2013) article titled *Design Ecosystems: Customising the Architectural Design Environment with Software Plug-ins.* They argue in favor of a design environment that makes it possible to connect various tools together in contrast with traditional self-sustained CAD environments.

Imagination stimulation: This theme emerged through the investigation of Picon (2003) ideas in section 2.4 The Act of Architectural Design and Visualization. He argues that through a paradigm shift in the definition of architecture by the eighteenth century, imagination becomes “man’s ultimate creative faculty” (2003, p. 297) and the driving force of mental image production. The theme was also discussed as a critique to Coley and Schukat (2002) study by pointing out that the proposed algorithm is significantly restricting the users’ imagination when it comes to criteria other than those discussed in the study since they cannot modify the algorithm’s proposals.

Interface: This theme emerged through discussion of Lightsolve, a lighting design program proposed in a study by Andersen et al. (2008). For instance, it was suggested that the Lightsolve working interface remains as a detached analysis environment which interrupts the design process flow.

Iteration: The iterative characteristic of the design process was discussed in detail in section 2.2 Design Process. For instance, Lawson (2006) names three iterative design process activities; analysis, synthesis, and evaluation. It is also discussed as a critique of the Lightsolve interface, proposed by Andersen et al. (2008). It was mentioned that the report that is produced by the Lightsolve working interface is neither real-time nor in the same working environment that the architect usually works in, so the architect needs to study the report and modify the design in its native working environment and then import it again to the Lightsolve working interface for the second round of analysis and so forth.

Knowledge acquisition: This theme was the central subject of the investigation in section 2.6 Knowledge.

Multiple levels of abstraction: Cross points out that "[using sketches,] designers think about the overall concept and at the same time think about detailed aspects of the implementation of that concept." (2006, p. 37) He argues that this feature in sketches "enable[s] designers to *handle different levels of abstraction simultaneously*." (2006, p. 37)

Pedagogic tool: Andersen et al. (2008) propose a hypothetical goal-driven design support expert system. (2008, pp. 603–604) The authors imagine an environment that enables them to set several goals, based on the reports provided by Lightsolve, and the expert system proposes several different strategies for achieving each goal. The architect is then able to manipulate the model inside the same environment and run the analysis process again. The authors believe that such an environment would imitate the same "interaction a designer would have with a consultant, making it conducive to a more natural design process". (Andersen et al., 2008, p. 603)

Real-time feedback: This theme emerged as a critique of the Lightsolve interface, proposed by Andersen et al. (2008). It was mentioned that the report produced by the Lightsolve working interface is neither real-time nor in the same working environment that the architect usually works in, so the architect needs to study the report and modify the design in its native working environment and then import it again to the Lightsolve working interface for the second round of analysis and so forth. It is concluded in section 2.5 Qualitative and Quantitative Criteria During the Design Process that there is a need for a real-time integrated design environment that provides the architect with the necessary analytical data, in an appropriate graphical manner.

2.9. Summary

In the first section, I investigated the design process and different models that are proposed for representing it. I reviewed the main characteristics of the design process, also connecting them to different models that are proposed for representing the design process, and the implications for each. I argued that in most of these models, the reciprocating characteristic of the design process is neglected. On this basis, I have proposed a model to emphasize the reciprocating characteristic of the design process.

Next, I provided a brief history of digital tools in architectural design. I studied the roots of CAD in both academia and industry. From there, I focused mostly on software that are popular today both in architecture schools and practice, and, therefore, I am studying in this research. As it is evident in this section, many of the matters that have been historically raised about the use of computers in the design process, are still subject to debate today.

In the next section, I addressed the distinction between the act of architectural design and visualization. In this section, relying on logical argumentation, I have debated in favor of the pivotal role of imagination during the act of architectural design, as the driving force of mental image production. I have also addressed the implications of this argument for tools, both digital and manual, which are used by architects.

In the following section, I investigated previous researches that have a strong theme of simultaneously addressing qualitative and quantitative criteria during the design process. I concluded that representing quantitative criteria, graphically, seems to be a more successful design approach, compared to quantifying qualitative criteria. I also pointed out some of the shortcomings, evident in the design environments which I reviewed in this section, including limited interaction with the architect, and the lack of a real-time integrated and graphical analytical tool. I have also mentioned the lack of phenomenological studies of qualitative aspects in these studies.

From there, I focused on two themes of my research questions: the concept of knowledge and the way it relates to architecture pedagogy and adaptation of new digital tools, and the concept of visual comfort in architectural design and specifically, the problem of glare as a good example of where qualitative and quantitative decision-making becomes critical. In the first section, I investigated the importance of tacit knowledge and especially, procedural knowledge in the adaptation of new digital tools. In the next section, after providing a summary of glare definitions and different ways of categorizing it, I focused on various factors that impact the perception of glare. The most important one for my research is the effect of an interesting view on reducing the perception of glare. To finish this section, I provided a comparison between various metrics used for glare analysis.

3. Methodology

3.1. Introduction

In this research, I have proposed a framework to support simultaneously addressing qualitative and quantitative criteria while designing apertures in the building envelope during the early stages of the design process. As presented later, I have covered, both, the best configuration of the available tools and the description of the ideal working environment, which enables architects to simultaneously address qualitative and quantitative criteria such as view and glare while aiming for sustainability and placemaking in their designs.

To do so, I went through four steps, which at the end of each step a revised version of the framework emerged. The framework emerging from the first step was revised during the following steps and the fourth and final step served as a consensus convergence step, finalizing the framework. These multiple steps were intended to triangulate the research design. Each step will be discussed in further detail in the following sections. Moreover, Figure 3-1 represents the general scheme of the research design. As seen below, the research design generally relied on qualitative methods of inquiry. Therefore, the following section establishes the appropriateness of the qualitative research approach and its philosophical assumptions as they relate to this research.

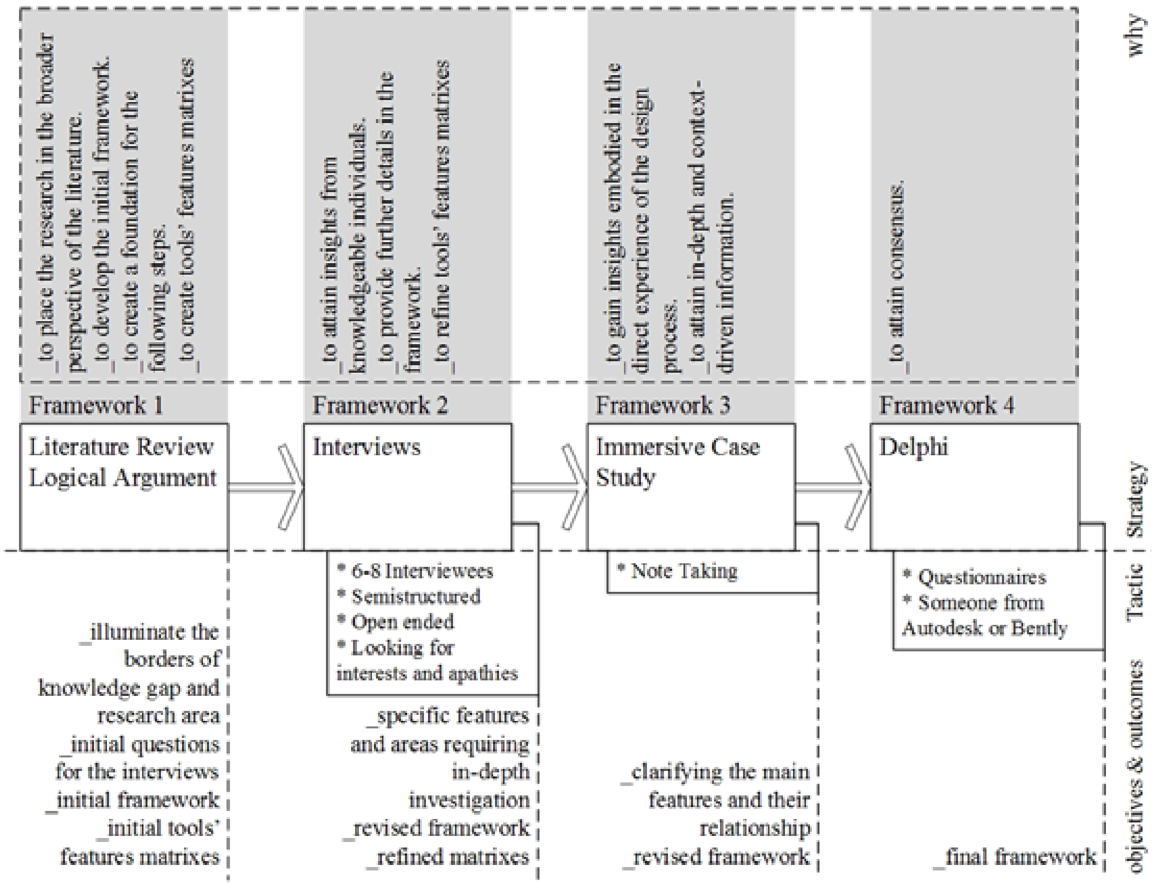


Figure 3-1 General scheme of the research methodology

The flowchart presented below as Figure 3-2, provides a roadmap of different sequential stages that I went through during this research. It also offers a clear outline of the research methodology.

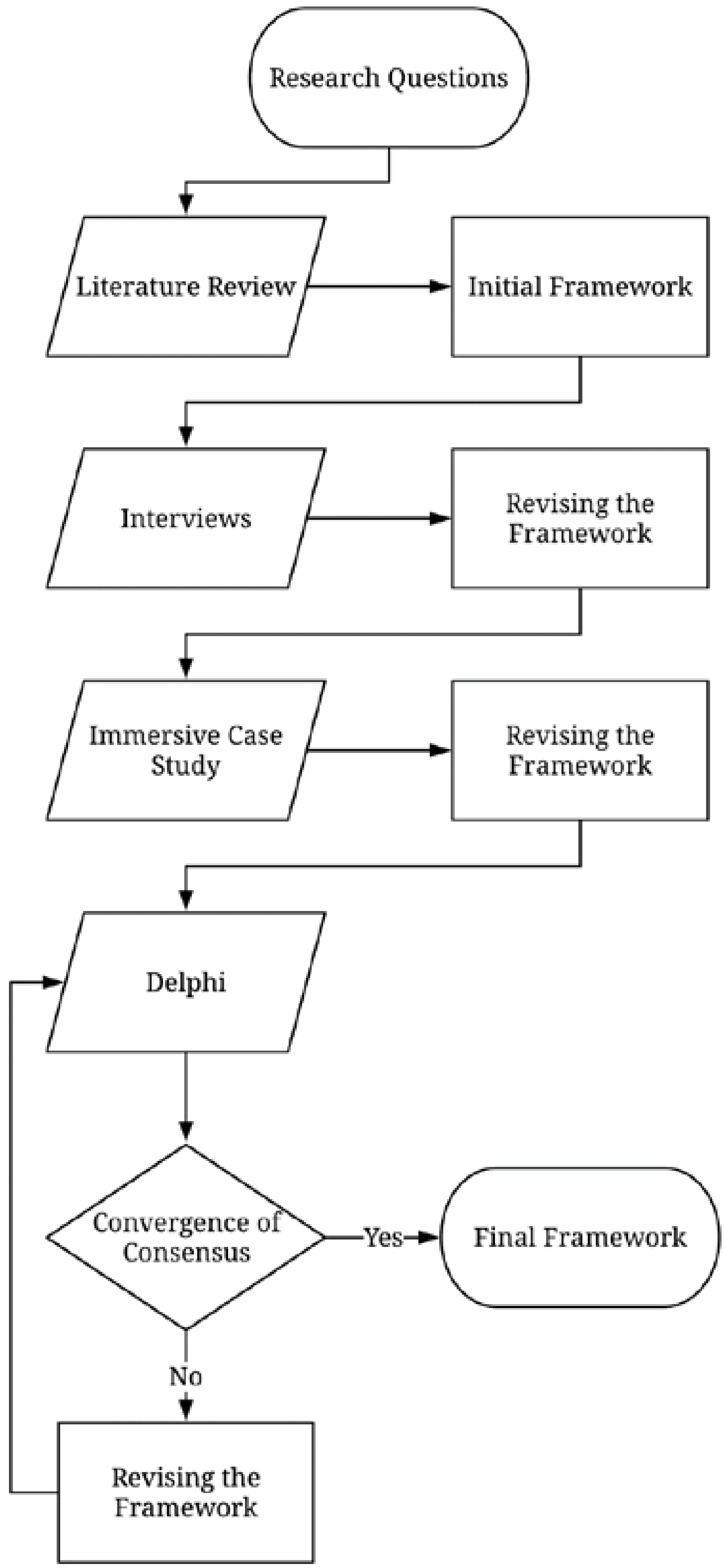


Figure 3-2 Research methodology flowchart

The analysis method used in this research includes a matrix in which the rows indicate the tools that were considered, and the columns show either the features and characteristics that support simultaneously addressing qualitative and quantitative criteria or the features and characteristics that limit this process. Each step, mentioned in the methodology, was intended to help to fill this matrix. Therefore, as the research proceeded, this matrix became populated with more features and characteristics. A schematic presentation of this process is shown in Figure 3-3.

This method of analysis corresponds with what Evers and Staa (2010) argue to be “The Miles and Huberman Tradition” in qualitative analysis. They state that the Miles and Huberman “analytic strategy entails the use of matrixes, charts, and other forms of graphic representation. Instead of filling these with numbers, as a quantitative researcher would do, a qualitative data matrix contains text fragments, key words, or full quotations.” (2010)

This approach provided guidelines that informed the immersive case study step based on the information which was obtained during the literature review and the interviews. These guidelines obviated the need for my proficiency with every one of the available tools.

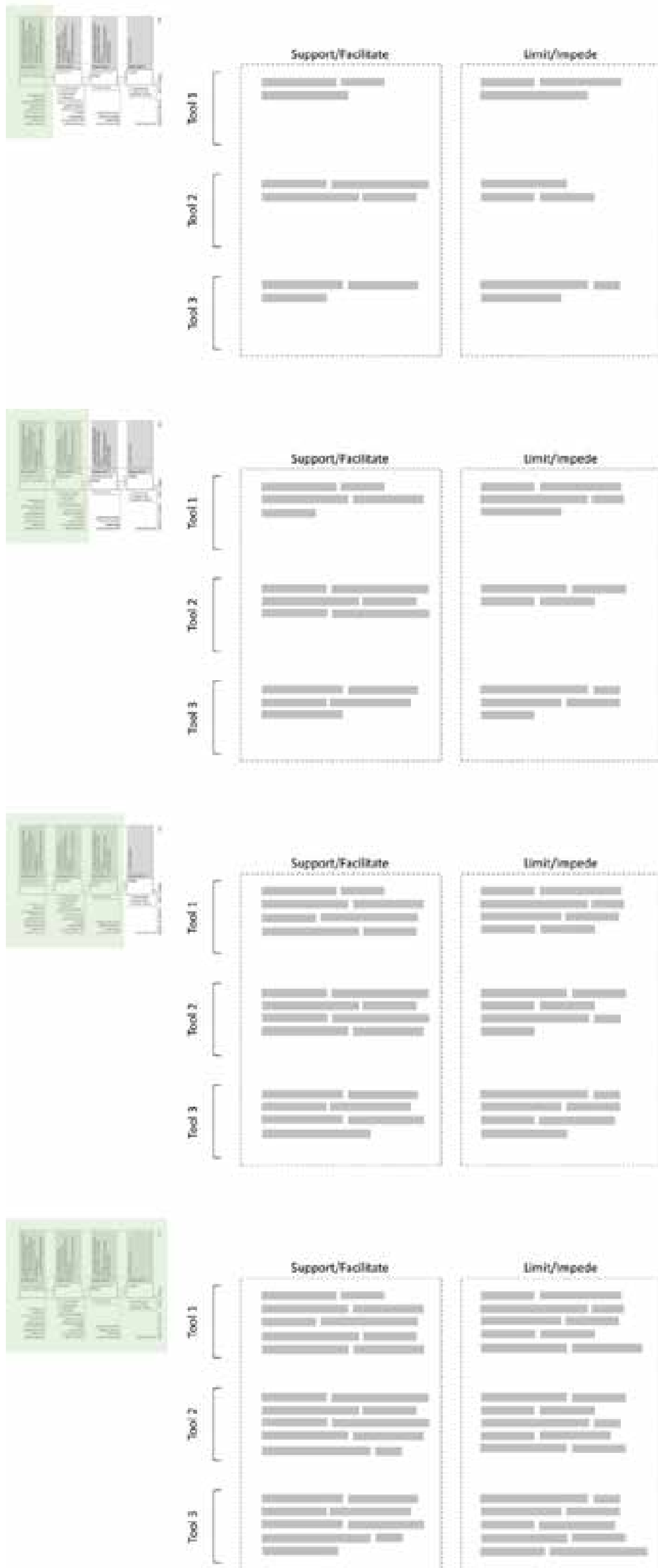


Figure 3-3 Schematic presentation of the analysis method

3.2. Qualitative Research

After providing a brief history of qualitative research and its roots in colonialism, Denzin and Lincoln, in their reputable handbook on qualitative research, offer the following generic definition:

> *"Qualitative research is a situated activity that locates the observer in the world. It consists of a set of interpretive, material practices that make the world visible. These practices transform the world. They turn the world into a series of representations, including field notes, interviews, conversations, photographs, recordings, and memos to the self. At this level, qualitative research involves an interpretive, naturalistic approach to the world. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret, phenomena in terms of the meanings people bring to them." (2005, p. 3)*

To gain a clear understanding of the reasons for which this research is committed to qualitative research, as a method of scientific inquiry, it is essential to illustrate the fundamental characteristics of the qualitative research approach. The most predominant characteristics have been already mentioned in the definition above, but to review these characteristics more easily, it is beneficial to refer to Groat and Wang (2013, pp. 218–223) for a shortlist of these characteristics:

An Emphasis on Natural Settings: "By 'natural settings' is meant that the objects of inquiry are not removed from the venues in which they typically exist as part of everyday life." (2013, p. 218) Also, the researcher uses "research tactics that engaged people within the context being studied, while the context itself was studied in its natural state." (2013, p. 219)

A Focus on Interpretation and Meaning: The researchers "not only ground their work in the empirical realities of their observations and interviews, but they also make clear that they, as researchers, play an important role in interpreting and making sense of that data." (2013, p. 219)

A Focus on How the Respondents Make Sense of Their Own Circumstances: "the researchers aim to present a holistic portrayal of the setting or phenomenon under study as the respondents themselves understand it." (2013, p. 219)

The Use of Multiple Tactics: "qualitative researchers will employ a range of tactics that are both particular to the context being studied, and of course appropriate to the research question(s) being asked. […] in research studies where one primary mode of inquiry is used, secondary tactics are typically employed." (2013, pp. 219–220)

Significance of Inductive Logic: "the research questions investigated through a qualitative study frequently evolve in an iterative process." (2013, p. 220)

Groat and Wang, also mention other characteristics of qualitative research including: Holistic, Prolonged Contact, Open-Ended, Researcher as Measurement Device, Analysis through Words or Visual Material, and Personal or Informal Writing Stance. (2013, p. 223) Creswell indicates "theoretical lens" as another fundamental characteristic of qualitative research, pointing out that "Qualitative researchers often use a lens to view their studies, such as the concept of culture, or gendered, racial, or class differences from the theoretical orientations." (2007, p. 39)

These characteristics give a clear vision about the reasons this research is based on qualitative methods of inquiry. I have tried to create a "holistic understanding" of digital tools and their use inside the architecture community. I have achieved this goal by studying this phenomenon in its "natural setting" and not through controlled experiments. At all the stages of this research, "the researcher is the principal measurement device." This fact is more evident in the immersive case study phase. Also, it has been important for me to understand how architects "make sense of their own circumstances." I employed multiple tactics for answering research questions, including interviews, immersive case study, and the Delphi method. And as mentioned before, this research being exploratory research, I relied heavily on “inductive logic” and the research questions were allowed to evolve during the research process.

3.2.1. Grounded Theory

Groat and Wang explain that “grounded theory seeks to investigate a setting holistically and without preset opinions or notions.” (2013, p. 234) Grounded theory is a relatively new approach. Historically, “the term grounded theory has been particularly associated with the work of sociologists Barney Glaser and Anselm Strauss, who first articulated this approach in the late 1960s and the 1970s.” (Groat & Wang, 2013, p. 235)

Kathy Charmaz in one of the sections of the Denzin and Lincoln’s handbook dedicated to grounded theory (2005, p. 507) argues that “The term "grounded theory" refers both to a method of inquiry and to the product of inquiry. However, researchers commonly use the term to mean a specific mode of analysis”. She later defines grounded theory as “a set of flexible analytic guidelines that enable researchers to focus their data collection and to build inductive middle-range theories through successive levels of data analysis and conceptual development.” She simplifies this definition and explains that “Grounded theory methods consist of simultaneous data collection and analysis, with each informing and focusing the other throughout the research process. As grounded theorists, we begin our analyses early to help us focus further data collection.” (Denzin & Lincoln, 2005, p. 508)

It is hard to provide an all-inclusive definition for grounded theory (GT). Ralph et al. (2015) point out that “New interpretations of GT methodology have arisen throughout its brief yet rich history. The differences in these interpretations have led to an ongoing and robust debate among grounded theorists." Charmaz points out that "Grounded theory marries two contrasting— and competing— traditions in sociology as represented by each of its originators: Columbia University positivism and Chicago school pragmatism and field research." (2006, p. 6) To be more specific, "While Glaser's background in quantitative empiricism led to codified methods and terminologies, Strauss's background in the more interpretive traditions in sociology led to a focus on the dynamic processes by which people interpret meaning and enact change." (Groat & Wang, 2013, p. 235)

Since the approach in this research is more in line with Strauss's view towards grounded theory, it would be beneficial to refer to Strauss and Corbin's definition of grounded theory: "In this method, data collection, analysis, and eventual theory stand in close relationship to one another. A researcher does not begin a project with a preconceived theory in mind (unless his or her purpose is to elaborate and extend existing theory). Rather, the researcher begins with an area of study and allows the theory to emerge from the data." (1998, p. 12)

In this research, I did not have any hypothesis or prior assumptions about features and characteristics of the tools that architects use and whether they support or limit simultaneously addressing qualitative and quantitative criteria. I tried to study this situation holistically and allow these features and characteristics to emerge from the data. As described in the introduction to this section, in this research, data collection and analysis happened simultaneously, and the framework expanded as the research proceeded. Also, each step of the methodology was intended to "inform and focus" data collection and analysis in the following steps.

3.2.2. Phenomenology

Groat and Wang argue that: “phenomenology emphasizes the holistic depth of the participant’s or author’s experiences; from them, generalizations are made about the essence of such experiences.” (2013, p. 95)

Seamon’s (2000) provides three categories of phenomenological research in the field of architecture: first-person phenomenological research; existential-phenomenological research; and hermeneutical-phenomenological research. However, he emphasizes that “very often the phenomenological researcher uses the first-person, existential, and hermeneutic approaches in combination”.

He describes the first-person approach as: “the researcher uses his or her own firsthand experience of the phenomenon as a basis for examining its specific characteristics and qualities”. Explaining the strengths of this approach, he argues that “if the phenomenologist has access in her own experience to the phenomenon she plans to study, first-person research can offer clarity and insight grounded in one's own lifeworld.”

Existential-phenomenological research is based on “the specific experiences of specific individuals and groups involved in actual situations and places.” In other words, the researcher studies respondents’ recollection of a phenomenon. von Eckartsberg (1998, pp. 22–23) defines four steps in conducting existential-phenomenological research. Seamon summarizes it as follows:

> *“identifying the phenomenon in which the phenomenologist is interested; gathering descriptive accounts from respondents regarding their experience of the phenomenon; carefully studying the respondents' accounts with the aim of identifying any underlying commonalities and patterns; and presentation of findings, both to the study respondents (in the form of a ‘debriefing’ about the study in ordinary language) and to fellow researchers (in the form of scholarly presentation).” (2000, p. 165)*

Hermeneutics is often defined as “theory and practice of interpretation” (Mugerauer, 1994, p. 4). The third approach, hermeneutic-phenomenological research, aims at interpreting and gaining “an understanding of material environments, whether furnishings, buildings, cultural landscapes, settlement patterns, and the like”. (Seamon, 2000, p. 167) More than any definition, the term “hermeneutic reading of buildings”, used by Seamon, clarifies this approach.

In this research, I relied on a combination of first-person and existential phenomenological research. At the interviews phase, I tried to gain insights about knowledgeable individuals’ experiences with digital tools during the design process. On the other hand, during the immersive case study phase, I used my own firsthand experience of using digital tools during the design process as a basis for examining their strengths or limitations on simultaneously addressing qualitative and quantitative criteria.

3.3. Methods

3.3.1. Logical Argument

Groat and Wang argue that the most basic characteristic of logical argument is “enumeration of first principles.” (2013, p. 379) They clarify it by pointing out that “A first principle is a fundamental proposition that is so self evident that it need not be derived from even more elemental proofs.” (2013, p. 379) They propose a schematic diagram (Figure 3-4) presenting the spectrum of logical argumentation typologies in architectural research.

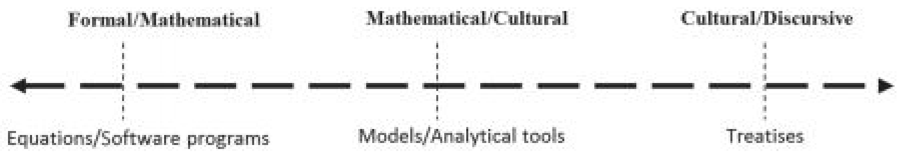


Figure 3-4 Spectrum of logical argumentation (Groat & Wang, 2013, p. 387)

On the left side, there are formal/mathematical arguments. Groat and Wang explain that “ ” (2013, p. 386) On the other side, there are cultural/discursive arguments. Groat and Wang argue that these are systems of logical argumentation that “have persuasive force because they capture some aspect of a large cultural worldview distilled into a ‘logical’ argument with both theoretical clarity and rhetorical power.” (2013, p. 387) They point out that “ architectural theories tend to reside at the cultural/discursive end of the logical spectrum.” (2013, pp. 384–385) For this reason, the logical argumentation used in this research falls on the cultural/discursive side of this spectrum. In between these two sides of this spectrum, falls the “logical frameworks that share characteristics of both formal/mathematical systems and cultural/discursive ones.” (Groat & Wang, 2013, p. 386)

In this research, I used logical argumentation to extract the first set of features and characteristics which support or limit simultaneously addressing qualitative and quantitative criteria during the early stages of the design process and to form the first outline of the framework. This logical argumentation is based on the findings of the literature review.

3.3.2. Interviews

The interview is a well-established method of inquiry, especially in qualitative research. Yet, providing a definition for it is fundamentally dependent on the researcher’s epistemological paradigm. Bailey (2007) defines interview as “Asking questions for the purpose of seeking information directly related to the research.” Maccoby and Maccoby (1954) define it as “A face to face verbal exchange, in which one person, the interviewer, attempts to elicit information or expressions of opinion or belief from another person or persons.”

On the other hand, researchers leaning more towards constructivist or critical paradigms, suggest a different power dynamic in the act of interviewing. Kvale and Brinkmann (2009) define interview as “An interchange of views between two persons (or more) conversing about a theme of mutual interest.” Fontana and Frey (2008) argue that “Two (or more) people are involved in this process, and their exchanges lead to the creation of a collaborative effort called the interview.”

As discussed before, my research followed a constructivist paradigm. Therefore, my understanding of the interview as a research method was more inclined towards definitions such as those of Kvale and Brinkmann or Fontana and Frey, where the interviewer and the interviewee(s) create meaning together.

In a general sense, interviews are usually categorized into three groups: unstructured, semistructured, and structured. Table 3-1 provides an overview of each of these approaches’ characteristics. Due to the explanatory characteristic of my research, I applied semistructured interviews. This approach provided the necessary flexibility and interactivity while preserving an overarching structure in the interview. While remaining focused on the organized topics, included in the interview guide, semistructured interviews enabled the interviewees to have the freedom to investigate the topics that emerge during the interview, through their own point of view, so they provided insights that were different from my understanding of the situation.

Table 3-1 Three categories of interviews based on (Bailey, 2007; Brinkmann, 2014; Fontana & Frey, 2008)

Unstructured	Semistructured	Structured
• informal • similar to a conversation • flexible • little standardization • evolves vs. Planned • rarely scheduled • not equally distributed • reciprocal process • more honest, morally sound, and reliable since treats respondents as an equal, let them express personal feelings: more realistic picture • does not guarantee fruitful information	• some level of flexibility • interview guide • specific questions organized by topics • no necessary order (flow of the interview) • scheduled with an expected timeframe • interactive: dialogue (based on the paradigm)	• determined questions, order, and pace • usually scheduled • flexibility is not a key feature • comparing answers • possibility of transforming into quantitative data and using statistical techniques for analysis • frequencies

Determining the number of interviewees in qualitative research is not a straightforward task. Baker et al. (2012) asks several experts in qualitative research "how many qualitative interviews is enough?" and report that the response is usually "it depends". Patricia A. Adler, and Peter Adler, answering this question, point out that "Qualitative researchers, working in the context of discovery, are more open-ended, and often follow emergent empirical and conceptual findings in unexpected ways. Thus, they may not know, in advance, how much data they need to gather." They conclude "The best answer is simply to gather data until empirical saturation is reached; however, this is not always possible or practical." (Baker et al., 2012, p. 8) Providing the same idea, in simpler words, Harry Wolcott argues that "For many qualitative studies one respondent is all you need – your person of interest. But in general, the old rule seems to hold that you keep asking as long as you are getting different answers". (Baker et al., 2012, pp. 3–4) Patton provides the same idea, writing: "There are no rules for sample size in qualitative inquiry. Sample size depends on what you want to know, the purpose of the inquiry, what's at stake, what will be useful, what will have credibility, and what can be done with available time and resources." (2001, p. 244)

The concept of data saturation has been developed originally by Glaser and Strauss (1967) as part of the grounded theory. They argue that "The criterion for judging when to stop sampling the different groups pertinent to a category is the category's theoretical saturation." (1967, p. 61) They provide a definition by pointing out that "Saturation means that no additional data are being found whereby the sociologist can develop properties of the category. As he sees similar instances over and over again, the researcher becomes empirically confident that a category is saturated." (1967, p. 61)

Glaser and Strauss also argue that saturation can only be reached through simultaneous collection and analysis of data. (1967, p. 61) They provide methodological guidance for identifying data saturation by pointing out that "When saturation occurs, the analyst will usually find that some gap in his theory, especially in his major categories, is almost, if not completely filled." (1967, p. 61) They explain that "The criteria for determining saturation, then, are a combination of the empirical limits of the data, the integration and density of the theory, and the analyst's theoretical sensitivity." (1967, p. 62)

Hennink, Kaiser, and Marconi (2017) provide future details to the concept of data saturation by defining two approaches to assessing saturation: code saturation and meaning saturation. They define code saturation as the point where all the themes are identified. On the other hand, meaning saturation is the point at which a rich understanding of the issues is developed. They highlight multiple parameters that influence saturation (Figure 3-5). They point out that "Each parameter acts as a fulcrum and needs to be 'weighed up' within the context of a particular study. A sample size is thus determined by the combined influence of all parameters rather than any single parameter alone.” (2017, p. 605)

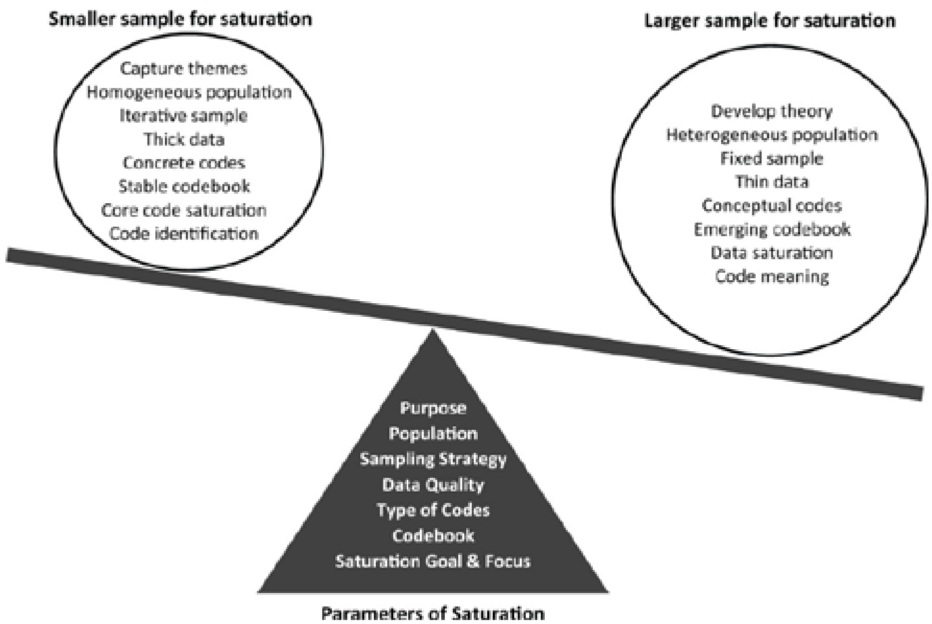


Figure 3-5 Multiple parameters influencing saturation. Source: (Hennink et al., 2017)

Based on the initial framework that emerged from the previous step, I conducted six interviews, trying to attain insights from knowledgeable individuals and provide further details in the framework. Through this number of interviews, I was able to both, achieve data saturation, and aim for a practical goal considering a PhD dissertation timeframe and budget limits.

Arguing based on Hennink, Kaiser, and Marconi parameters, since I was aiming at a relatively homogeneous population and the interview was not my only method of data collection and the codes that emerged from interviews were further developed during the immersive case study and Delphi method steps, I was able to reach saturation with relatively small sample size.

Additionally, Mason (2010) studying the sample size and saturation in PhD studies using qualitative interviews, collects various guidelines from different publications based on the research theoretical framework. He reports that these guidelines argue in favor of smaller sample size (starting from five) for researches, like this research, that follow a phenomenological theoretical framework.

Patton (2001) provides two general sampling strategies: random probability sampling and purposeful sampling. He argues that purposeful sampling "Select information-rich cases strategically and purposefully; specific type and number of cases selected depends on study purpose and resources." (2001, p. 243) He argues that "information-rich cases are those from which one can learn a great deal about issues of central importance to the purpose of the inquiry… Studying information-rich cases yields insights and in-depth understanding rather than empirical generalizations." (2001, p. 230)

I selected the interviewees, following the purposeful sampling approach, from academia and professional practice. This included all the major stakeholders affected by the results of this research. The numeral distribution of the interviews was: 4 interviewees from academia and 2 interviewees from professional practice. (for more details about the interviewees refer to 4.2 The Interviewees)

Moreover, the interviews, alongside the immersive case study, were an investigation on the knowledge domain of the tools. The fundamental information regarding questions such as the minimum necessary knowledge to efficiently use a specific tool and the required depth of that knowledge were achieved at these stages.

3.3.3. Immersive Case Study

Robert Yin (2009, p. 18) provides the following definition for the case study as a research method: “A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and

context are not clearly evident.” Groat and Wang change this definition to “an empirical inquiry that investigates a phenomenon or setting” (2013, p. 418) to make it more applicable to architectural research.

Robert Stake, too, points out the importance of the context in choosing case study as a research method, arguing that: “For a qualitative research community, case study concentrates on experiential knowledge of the case and close attention to the influence of its social, political, and other contexts.” (2005, p. 444)

Groat and Wang summarize the major strengths of case study as: “Focus on the embeddedness of the case in its context, capacity to explain causal links, richness of multiple data sources, ability to generalize to theory, compelling and convincing when done well.” (2013, p. 441) On the other hand, they point out that with each of these strengths, comes a weakness: “Potential for overcomplication, causality likely to be multi-faceted and complex, challenge of integrating many data sources in a coherent way, replication required in other cases, difficult to do well; fewer established rules and procedures than other research designs.” (2013, p. 441)

Ridder (2017) describes four different case study designs: no theory first, gaps and holes, social construction of reality, and anomalies. He argues that the “no theory first” design, tries “to capture the richness of observations without being limited by a theory”. (2017) On the contrary, the “gaps and holes” design aims “at specifying gaps or holes in existing theory with the ultimate goal of advancing theoretical explanations.” (2017)

The “social construction of reality” design, which Ridder believes Robert Stake is a good representative scholar of, follows a constructivist approach towards case study, in contrast to the past two designs which had positivistic assumptions. Ridder argues that in this approach “the purpose is not theory-building but curiosity in the case itself.” Or as Stake puts it: “The researcher examines various interests in the phenomenon, selecting a case of some typicality but leaning toward those cases that seem to offer an opportunity to learn… Potential for learning is a different and sometimes superior criterion to representativeness.” (2005, p. 451) As I have already discussed in previous sections about my epistemological orientations, my approach towards the case study is closer to this category.

The fourth design, “anomalies”, focuses on “what is interesting and what is surprising in a social situation that existing theory cannot explain.” Ridder argues that “An anomaly does not reject theory, but rather demonstrates that the theory is incomplete.”

Although the case study is a well-known research method, the term “immersive case study” may need more explanation. I see the relationship between case study and immersive case study close to the relation of ethnography and autoethnography. The Encyclopedia of Case Study Research defines autoethnography as “a form or method of research that involves self-observation and reflexive investigation in the context of ethnographic field work and writing.” (Maréchal, 2010) Based on this definition, I would define my approach towards immersive case study as a self-observing and reflexive investigation in the context of a specific design project tailored based on my research questions. This approach towards case study as a research method closely resonances with phenomenology as a theoretical framework for my research. (refer to section Phenomenology)

A common criterion in categorizing case study research is the number of cases being studied, single or multiple cases. Groat and Wang argue that in a single case study, the researcher "sought to investigate" phenomena "involving multiple and highly complex factors". Therefore, it is more important for the researcher "to uncover the very complex dynamics of one setting of interest than to limit the theoretical scope of the research by looking less deeply at more settings." (2013, p. 431) Exactly due to these reasons, I proposed a single case study for this research.

The chosen case study for this research was designing a community center for a housing project in Charlottesville, Virginia. This project was chosen because the program provided a good opportunity to investigate both qualitative and quantitative criteria. The project is located on a hilltop wooded site that provides unrestricted views in various directions. Also, since the project was intended to be an eco-friendly housing complex, the program required showcasing sustainable design strategies.

The immersive case study step provided me with the opportunity to gain insights that emerged from the direct experience of the design process while focusing on simultaneously addressing placemaking and sustainability criteria through simultaneous studies such as view and glare.

During the design process, different tools that were used as well as the purpose behind utilizing them and their strengths and limitations on achieving that purpose were documented. This information was used to demonstrate the strengths and drawbacks of current tools which are commonly used by architects during the design process. The information gained during the immersive case study was used to revise the framework as discussed in this chapter's introduction.

This method of analysis corresponds with what Evers and Staa (2010) argue to be "The Miles and Huberman Tradition" in qualitative case study analysis. Mile and Huberman "analytic strategy entails the use of matrixes, charts, and other forms of graphic representation. Instead of filling these with numbers, as a quantitative researcher would do, a qualitative data matrix contains text fragments, key words, or full quotations."

As mentioned in the interviews section, the immersive case study, alongside the interviews, was an investigation of the knowledge domain of the tools. The fundamental information regarding questions such as the minimum necessary knowledge to efficiently use a specific tool and the required depth of that knowledge were achieved at these stages.

3.3.4. Delphi Method

Historically, the Delphi method was proposed by Norman Dalkey and Olaf Helmer in an article titled "An Experimental Application of the Delphi Method to the Use of Experts", published in 1963. The article journals a study named "Project Delphi" conducted by the RAND Corporation. The subject of that study has been "to apply expert opinion to the selection, from the viewpoint of a Soviet strategic planner, of an optimal U. S. industrial target system and to the estimation of the number of A-bombs required to reduce the munitions output by a prescribed amount." (Dalkey & Helmer, 1963)

Dalkey and Helmer define the objective of the Delphi method as "to obtain the most reliable opinion consensus of a group of experts" through "repeated individual questioning of the experts (by interview or questionnaire)" while avoiding "direct confrontation of the experts with one another.” (1963, p. 458) The authors argue that this controlled indirect interaction between the experts provides a platform to acquire not only the opinion of the experts regarding a specific problem but also their reasoning and the set of factors they consider relevant while providing them with the opportunity to correct their misconceptions and draw their attention to other factors which they may have overlooked.

Since then, as Linstone and Turoff (1975, p. 3) point out, the Delphi method has been used in numerous researches. As they argue “The technique and its application are in a period of evolution, both with respect to how it is applied and to what it is applied.” (1975, p. 3) For this reason, they provide a new definition of the Delphi method, which is broader and more flexible: “Delphi may be characterized as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem.” (1975, p. 3)

Linstone and Turoff define two tracks of development within researches that utilize the Delphi method: the initial consensus or Lockean Delphi, and the contributory or Kantian Delphi. (1975, p. 27) They argue that the consensus or Lockean Delphi is “characterized by a strong emphasis on the use of consensus by a group of *experts* as the means to converge on a single model or position on some issue.” (1975, p. 27) In contrast, the contributory or Kantian Delphi “allows many *informed* individuals in different disciplines or specialties to contribute information or judgments to a problem area which is much broader in scope than the knowledge that any one of the individuals possesses.” (1975, p. 27) They argue that contributory Delphi enables the researchers to achieve a “comprehensive overview of the issue”. (1975, p. 27)

This research, like most qualitative research, does not produce results that could be validated in the same manner as a positivistic/post-positivistic quantitative research. As Groat and

Wang argue (2013, p. 81) the tendency to do so, is a mistake. As a substitute for the concept of validity, they argue in favor of the concept of credibility. (2013, p. 81)

To achieve credibility, Guba (1981) proposes several solutions, the most important among them, based on Groat and Wang opinion (2013, p. 84), is data collection triangulation and *member checks*. Guba defines member checks as "testing the data with members of the relevant human data source groups." (1981, p. 80) Groat and Wang provide a more straightforward definition: "checking the data and interpretations with the respondents and groups from whom the data were solicited." (2013, p. 84)

The idea of member checks is closely similar to the idea of convergence of consensus, discussed in the starting paragraphs of this section. Fletcher and Marchildon (2014) point out this resemblance in the context of Participatory Action Research. They argue that "The Delphi method is an iterative approach to research in which participants are presented with regular reports on the findings during each questionnaire round. This provides them with the ability to confirm or revise their previous answers and ensures that participants remain connected to, and involved in, the development of the research." (2014, p. 4) As it is mentioned in Dalkey and Helmer's definition of the Delphi method above, obtaining consensus has been a central incentive for developing this research method from the beginning. Therefore, to achieve credibility, both by data collection triangulation and obtaining consensus, I utilized the Delphi method to finalize the framework.

Following on the argument above, about using the Delphi method to obtain consensus as member checks, my panel of experts were from the same group of people I referred to for the interviews. Therefore, the panel of experts included people from academia and professional practice. Again, this included all the major stakeholders affected by the results of this research.

The panel of experts consisted of seven individuals: five of them were university faculties from various architecture schools with research and teaching interests related to daylighting, digital tools, and the boundary between qualitative and quantitative assessments. Two of the experts were architects active in professional practice with previous experience in projects which had a strong emphasis on both qualitative and quantitative studies of the design problem.

Murry and Hammons (1995) provide a detailed description of the Delphi method common procedures. They point out that "The typical first-round questionnaire uses an open-ended format to elicit individual judgments or opinions from each member of the panel about the particular issue or problem under study." They explain the iterative nature of the Delphi method and describe this process as: "In the second-round questionnaire, the researcher requests the panel of experts to consider, to rank and/or rate, to edit, and to comment upon the responses developed during round one."

Brady (2015) points out that "While the Delphi method has been regularly utilized in mixed methods studies, far fewer studies have been completed using the Delphi method for qualitative research." Fletcher and Marchildon (2014) argue that "Although commonly perceived as a quantitative method because of its focus on statistical consensus, a modified and open-ended Delphi method facilitated a qualitative understanding". They provide recommendations "to researchers wishing to use the Delphi method qualitatively (i.e., without statistical consensus)". (2014, p. 1)

The Delphi panel consisted of two rounds of interactions. In the first round, an online presentation in the format of a website was shared with the participants. The online presentation provided a short description of the research questions, the methodology, and the findings (the framework). A detailed explanation of this presentation is provided in the section The Initial

Presentation. At the end of the online presentation, the participants were asked to answer two questions using an online commenting section:

1. Do you think this framework addresses all aspects of the problem? If not, what aspect is missing?
2. Do you agree with the categorization of the themes under this framework? If not, what changes do you suggest?

In the following round, a report of the comments (refer to the section The Report) was produced and sent to each participant for the second round of the Delphi panel. In response to this report, all seven participants (100%) indicated their approval of the applicability of the framework without further modifications.

4. Interviews

4.1. Introduction

As described in chapter three (methodology), I used the interview tactic as a qualitative method to attain a deeper understanding of preferences and common practices among architects regarding simultaneously addressing qualitative and quantitative criteria in the early stages of the design process and specifically their reasoning for their choices for the tools used. I conducted 6 interviews in total, 2 with architects in professional practice and 4 with architects in academia, serving in faculty positions.

The interviews were performed in a semi-structured manner. I referred to a list of questions (refer to Appendix A) during the interviews, but depending on the interviewees' responses, I occasionally asked other questions to clarify a response or changed the order of the questions to maintain the flow of the conversation. It was more important for me to sustain the dialogue with the interviewee rather than follow a preset order, since most of the time, if asked directly about their reasoning process, the interviewees would give stereotypical responses, however, if the question was asked while developing a conversation regarding that topic, the answers were more insightful and personal.

This chapter along with chapter five serves as the main results chapters. Therefore, the sections are outlined in an order which prioritizes clear referencing over the coherence of the chapter's text as one might read from the beginning to end. For a more coherent discussion of the themes next to each other, please refer to chapter 7 Conclusion.

4.2. The Interviewees

To maintain the anonymity of the interviewees, pseudonyms were used. The pseudonyms remained consistent throughout the data collection and analysis phases, and in this dissertation to help the reader to understand the similarities as well as differences between the interviewees' responses. Table 4-1 provides background information for all the interviewees and is intended to help the reader to put the direct quotations from the interviewees in context.

Table 4-1 Interviewees Background Information

Name	Profession	Expertise
J	architecture professor (emeritus)	He has taught courses and studios with an emphasis on the integration of computing into the design process. Also, courses on computer programming, CAD systems, virtual environments, and Grasshopper.
V	architect	She is working in an international consulting firm, providing performance analysis feedback for architecture firms since 2016. Her PhD research involved the development of a digital tool (a decision-support software) for architects.
D	architecture professor	She is an assistant professor at a school of architecture since 2017. Her PhD research involved the development of a digital tool (a plugin for glare analysis) for architects.
E	architect	He is a project manager in an architecture firm with many medium-scale projects in the United States and Internationally. He has been active in practice since 2010.

B	landscape architecture professor	He has been teaching landscape architecture since 2004. His research is mostly focused on digital representation as well as real-time interactions between virtual and physical spaces. He has also published several books on these topics.
P	architecture professor	He has been teaching architecture since 2004. His research is mainly focused on the theoretical study of manual tools and architectural drawings. He has also published several books on these topics.

4.3. The development of the Themes

As the result of the interviews, the initial themes that emerged during the literature review were substantially expanded. As a result, understanding the relationship between these themes is no longer an easy task that can be done without the help of a diagram. Since, an important outcome of this research, beyond the development of these themes separately, is to gain a deeper understanding of thematic relationships and interconnections, it is important to understand these connections before moving on. Figure 4-1 illustrates these connections.

There are two factors in play that inform the development of these connections. One is the proximity of the emergence of these themes in an interview. In other words, if during the interview, the interviewee talks about one theme and then moves to another theme right after that, it suggests that there is a connection between these two themes. The other factor is the logical relationship of these themes in the context of the literature review. Therefore, the literature review helps to understand these emerging themes in connection to one another.

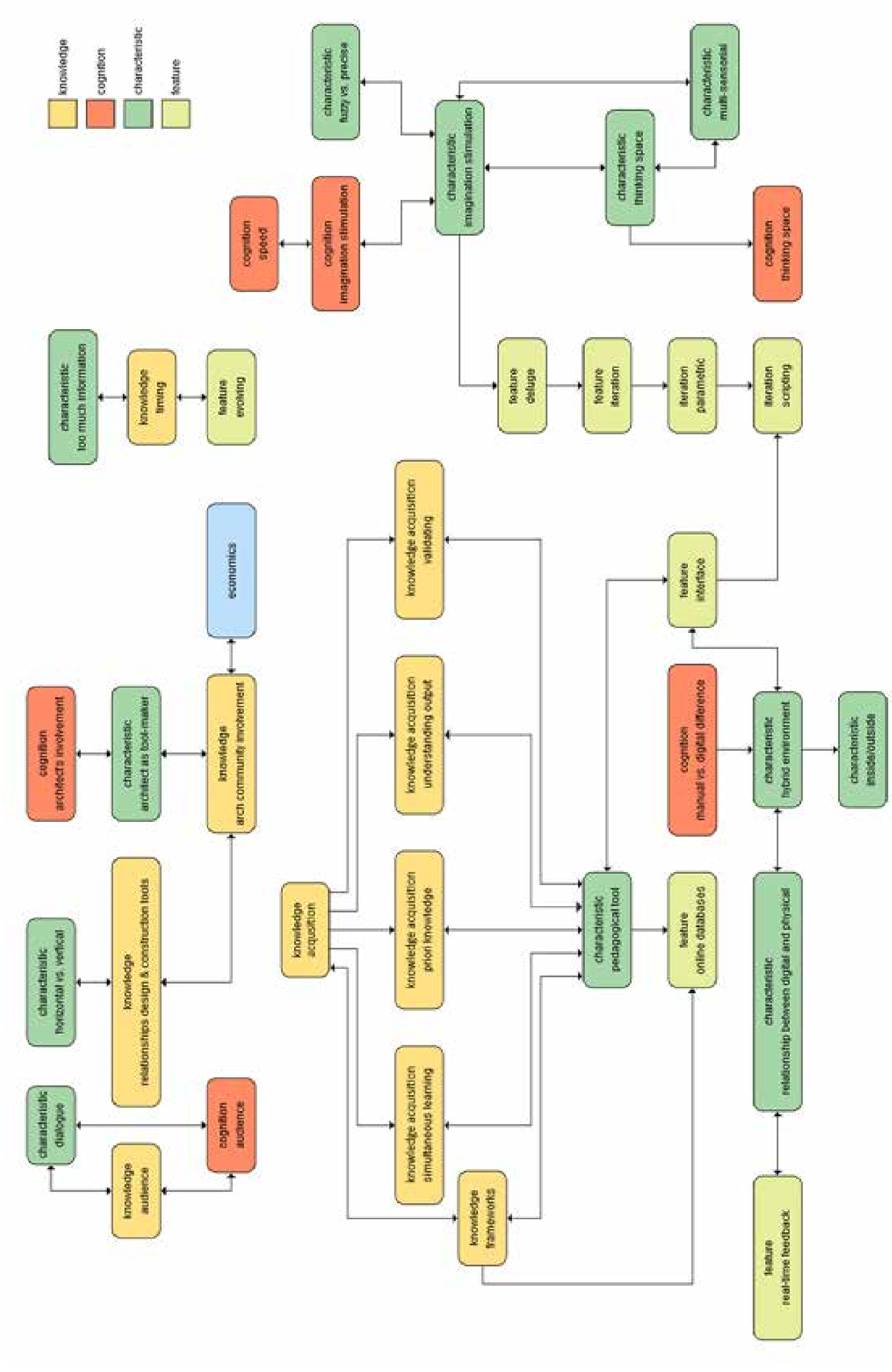


Figure 4-1 Themes interconnections at the end of the interviews

To achieve coherence while discussing each theme next to the others, design process stages (as discussed during the literature review) were introduced as a new dimension. The resulting diagram plays the role of an overarching structure which helps to map out each theme while maintaining the overall picture. This chapter, as well as the next chapter, are organized based on this structure and Figure 4-2 can be used as a road map while going through this chapter.

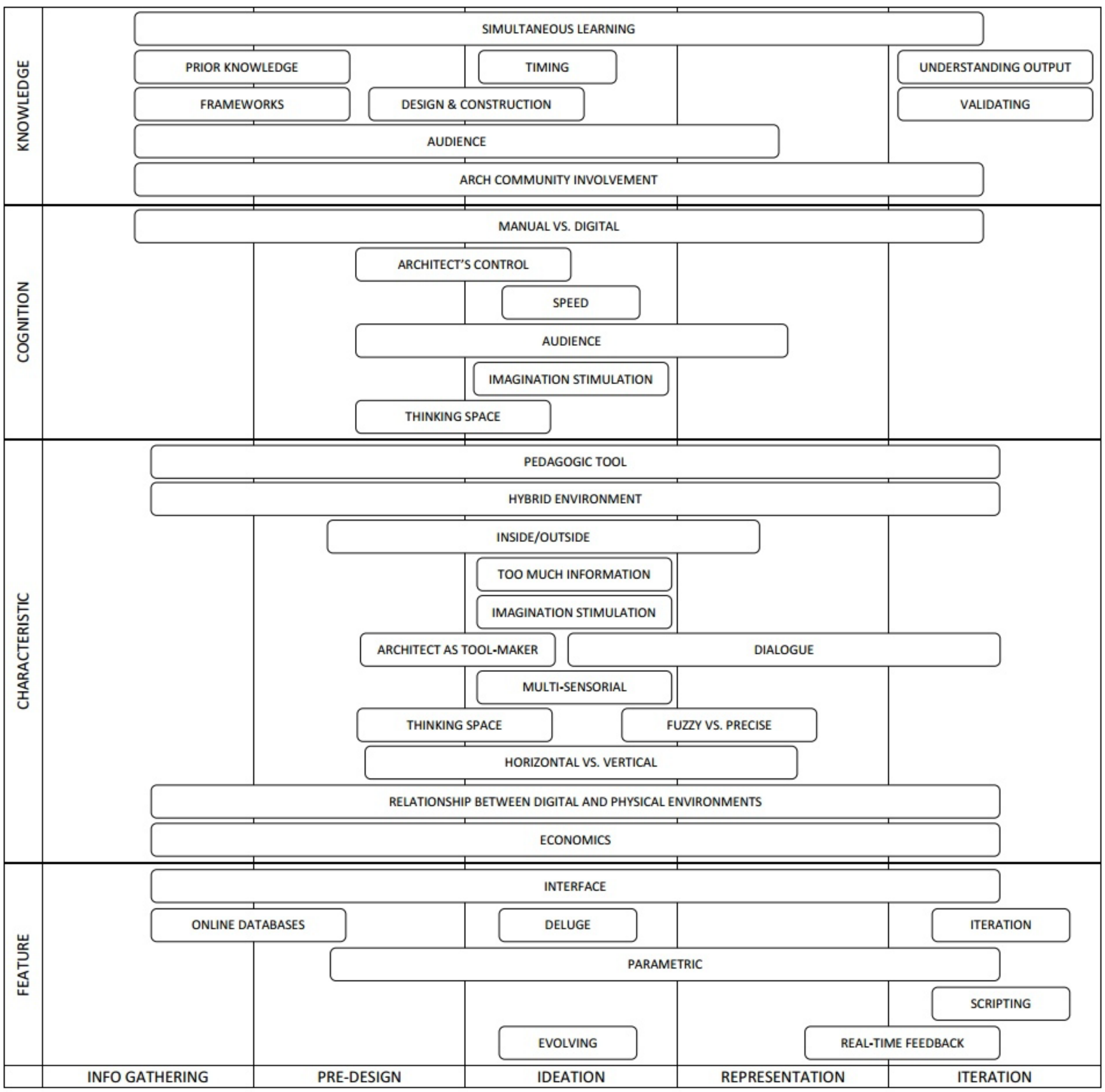


Figure 4-2 Themes in relation to design process stages at the end of the interviews

4.4. Knowledge - Ideation Themes

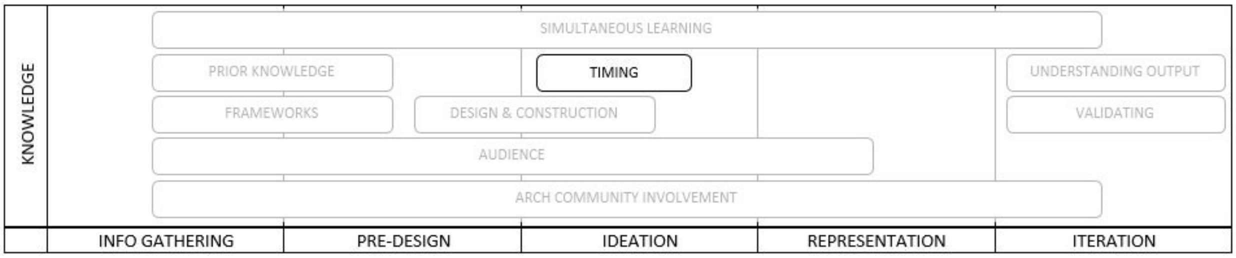


Figure 4-3 Knowledge - Ideation Themes

4.4.1. Timing

E mentions that for daylight analysis they use Sefaira during the early stages of the design process and later switching to Insight:

> *"Then you go to Insight and once you start using that the design is pretty much what it is so it's really just validating the work that was done in Sefaira early on […] but then so with that if we shrink the window size we run an analysis to see what that does to the daylighting within the space." (personal communication, December 4, 2018)*

It suggests that at each stage of the design, a tool, even with similar objectives, needs to have certain characteristics that correspond with the requirements of that stage of the design process. For instance, talking about Insight's characteristics, E mentions:

> *"The Revit plug-in for Insight is… can do those same things it's also more powerful so it's useful once the model gets really heavy and really developed but it can still do fine-grained analysis, which is good for LEED certification submission things like that it" (personal communication, December 4, 2018)*

While discussing Insight and Sefaira, he points out the problem that: "they don't always necessarily provide the right kind of feedback at the right time" (personal communication, December 4, 2018). This suggests that while using quantitative tools such as Insight and Sefaira, there is a "right kind of feedback" and a "right time" for it from the architect/user's point of view.

When developing such tools, the developer should contemplate what is the right feedback and when is the right time. To expand these questions, the developer should consider:

> What information should the architect know to be able to make related decisions?
>
> When (during the design process) would the architect need useful decision-support information that the tool can provide?
>
> Does the architect have access to information at the proper stage of the design process?

V mentions a similar observation but in a different way:

> *"When I say it takes me 3 weeks to do the model it does not mean that it will take me 3 weeks to run the script typically when you have 3 weeks-deadline you will be running the script maybe 2 or 3 days before you know why because people spend so much time to just convert that complex building into a simple building" (personal communication, November 10, 2018)*

Here, the problem is having too much information rather than not enough. The model is developed to a point with too much detail as input to the performance analysis tool.

4.5. Cognition - Ideation Themes

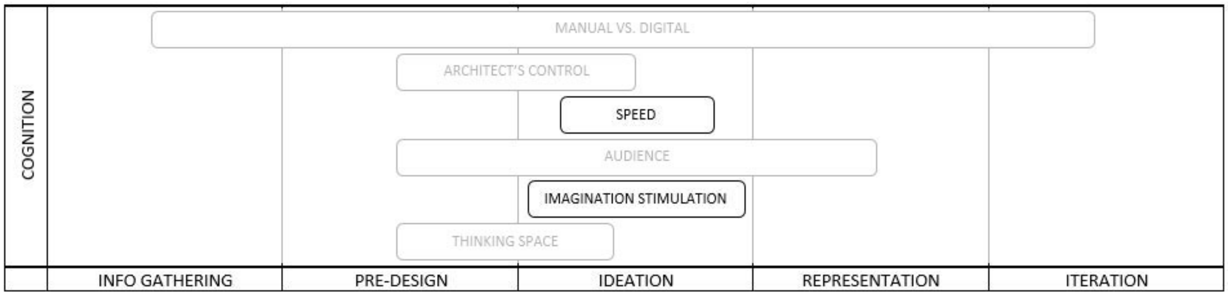


Figure 4-4 Cognition - Ideation Themes

4.5.1. Imagination Stimulation

As discussed in the literature review, commonly, there are two roles assigned to architecture drawings: representation of ideas and imagination stimulation. P argues that the role of imagination stimulation has been neglected in the development of the most currently available software for architects:

> *“how the active drawing helps architects to imagine their designs and I’m not quite sure where to start but a lot of the translation of architectural drawing into software didn't look at that question at all, it wasn't even raised as an issue it was more about the assumption that architectural drawings are transferring information and how is that information conveyed and there were remarkable achievements in aggregating and simplifying information transfer with architectural drawing in the computer but I think in general we really lost sight of its connection back to the architects' imagination, which is really the value that the architects add” (personal communication, January 16, 2019)*

Moreover, P argues that the architect’s imagination is his/her most important contribution to the design, and architecture tools should effectively support this:

> *“So that's the architects’ unique skill of imagining what could be and I think our drawings are ways of extending our mind, our imagination into the complexities of designing a building. So my main concern about the translation from hand tools to electronic tools is how they can aid the architect’s imagination so that the architect is engaged thinking about the design and helped to imagine what it would actually be like to build or to live in the design and in the end, I think that helps the architect to make better decisions to make more ethically justifiable decisions” (personal communication, January 16, 2019)*

4.5.2. Speed

B argues that “we can't take for granted the kind of efficiency, the speed of which we work, the kind of consistency with which we work.” (personal communication, December 4, 2018) This argument is similar to Williams and Tsien argument in their essay “On Slowness”. They explain their essay objective by pointing out that “We write not in opposition to computers […] but rather it is a discussion about the importance of slowness. We write in support of slowness.” (1999)

Explaining their decision-making process, Williams and Tsien argue that slowness is an important and inherent aspect of it: “When we make changes, they occur with effort and a fair amount of tedious scrubbing with erasers, erasing shields, and spit. We have to sift back through previous drawings and bring them to an agreement. So, decisions are made slowly, after thoughtful investigation, because they are a commitment that has a consequence.” (1999)

This suggests that there is a speed range for the design process and one cannot simply speed up the process without consequences. Many new digital tools, advocate for a faster and more efficient design process, without addressing the cognitive requirements of the human mind for highly imaginative and complex tasks.

4.6. Characteristics - Ideation Themes

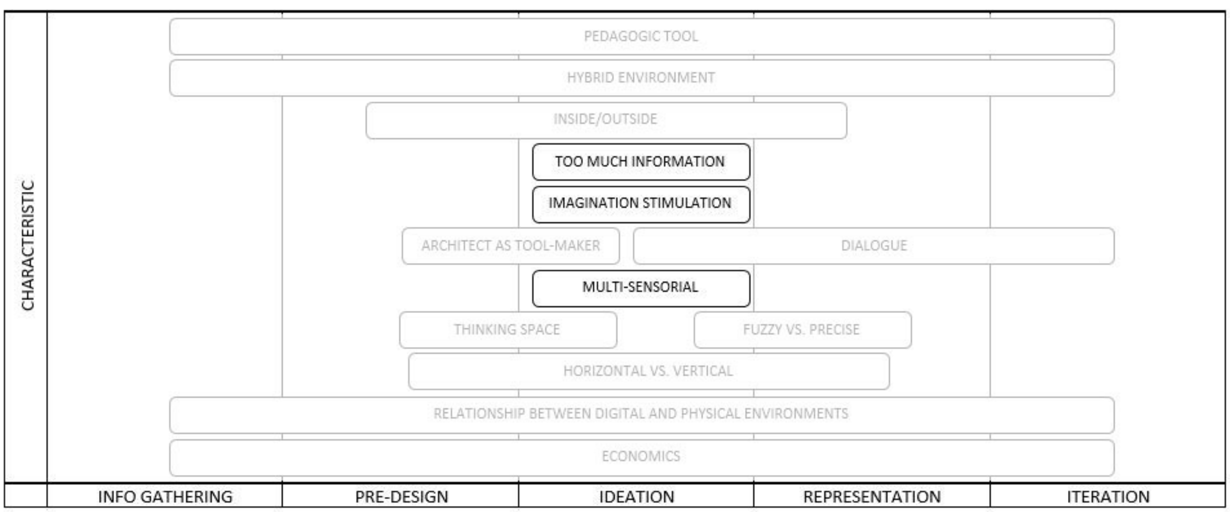


Figure 4-5 Characteristics - Ideation Themes

4.6.1. Imagination Stimulation

Similar to P, B mentions the two roles of design tools: representation and imagination stimulation. Regarding the latter, he argues that each architect, through his/her choice of tools, defines the design's problems:

> *"for me, there are two aspects to the tools we use in design. One of them is I would say more about representation. So it's about, it's about taking a design speculation, a proposal and, and building a package of drawings, documents, movies so that we can talk about that with people outside of us and our design team. And sometimes it's for designing but mostly it's for like an external audience. And so a lot of what we do is that in my opinion, it is about making drawings, making animations, making presentations to talk about our work. Internally, I think it becomes much more personal, it's about the design team or about you as a designer and the tools you put together in order to see the project through a certain lens and work through a series of design problems" (personal communication, December 4, 2018)*

In other words, B argues that by utilizing a certain tool, the architect defines the design problem in a certain way which results in a specific answer. P associates this connection between the design tools and the design answer to the role a tool plays in the stimulation of the architect's imagination:

> *"So, there is a strong multi-sensorial relationship between the activities of the traditional drawing and building and so when we use these tools, like when you sharpen a cedar pencil you get the smell of wood. So all of these things suggest architectural thinking that is very strongly linked to the multi-sensorial nature of the building site of experiencing environments in the built world, and so the ways that architectural drawing help to reinforce that aided the architects' imagination." (personal communication, January 16, 2019)*

P argues that the role of design tools as imagination stimuli has mostly been overshadowed by the tool as means to represent the idea. He argues hyper organization in tools such as BIM prevents imagination:

> *"in the sense that an architect can put many different lead points on a pencil to create different kinds of lines, we should be able to do that with computers too.*

So the more it's been pretty organized, like with BIM the less there is an opportunity for architectural imagination and the more it's about producing rather than imagining." (personal communication, January 16, 2019)

This argument is closely connected to the theme *Fuzzy versus Precise*.

4.6.2. Multi-sensorial

P argues that historically, the design environment has been a multi-sensorial experience for the designer:

> *"so there is all of this very much bodily interaction with the making of drawing materials and drawing tools so it's not something that's a premade thing that only does one thing you can drink the wine and then you can use some of that same wine to make the drawing ink." (personal communication, January 16, 2019)*

However, through time, other senses have become over-shadowed by vision, as Pallasmaa (2012) argues, which has led to many digital tools today lacking any sort of multi-sensorial characteristic. P argues that the multi-sensorial characteristic is supportive of the use of tools as the stimulus for the architects' imagination:

> *"So there is a strong multi-sensorial relationship between the activities of the traditional drawing and building and so when we use these tools, like when you sharpen a cedar pencil you get the smell of wood. So all of these things suggest architectural thinking that is very strongly linked to the multi-sensorial nature of the building site of experiencing environments in the built world, and so the ways that architectural drawing help to reinforce that aided the architects' imagination." (personal communication, January 16, 2019)*

P, providing the example of pressure-sensitive digital styluses, believes there are numerous opportunities to incorporate responses from other senses into digital tools:

> *"It strikes me that a lot of the things that haven't been attended to as much are some of those other sensory aspects. So how we deal with the tactility of the tool, the ability to show a change of pressure in the recording device so that you're not seeing the same line for varied expressions and there are lots of ways you*

can take that further but that's one example." (personal communication, January 16, 2019)

However, P believes that such embracing of other senses and aspects, requires a paradigm shift:

"I want to believe that with the delicacy of the computer there would be ways to get at all those different kinds of qualitative aspects, but it's going to require a different attitude on the part of programmers and the design of the interface with the computer. It's, it can't be the purely rationalized or realistic information-based idea about Cartesian space. It's gotta be the architectural space of engaging with the thing in all of its ramifications like we were talking about smell and taste and all that." (personal communication, January 16, 2019)

4.6.3. Too Much Information

V points out the problem of having to deal with too much information after the design is developed to a certain level. Talking about Revit models, she mentions that this tool provides no easy features to filter the huge amount of information that is produced during each design project:

"It takes me at least 3 weeks to do this model when I say it takes me 3 weeks to do the model it does not mean that it will take me 3 weeks to run the script typically when you have 3 weeks deadline you will be running the script maybe 2 or 3 days before you know why because people spend so much time to just convert that complex building into a simple building" (personal communication, November 10, 2018)

V argues that a plugin for Revit, using Dynamo scripting environment, that can convert a complex model to a simpler one that is suitable for running performance analyses would be desirable:

"somebody creates a code or a script in Dynamo which is like a plugin in Revit which you can use your entire building and convert it to a usable form of building structure because when you are doing daylight analysis you need a very simple basic model, you don't need all the, like slab information, you don't need that, so if someone can develop something like that where they can convert that complex model into a simple model" (personal communication, November 10, 2018)

4.7. Feature - Ideation Themes

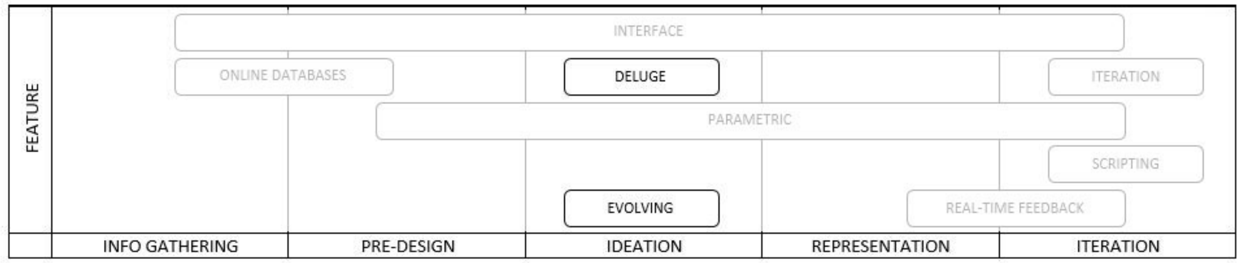


Figure 4-6 Feature - Ideation Themes

4.7.1. Evolving

E describes the evolving nature of the design process, explaining how the project evolves as more layers and considerations are added:

> *"you can have that object that is driven based like performance criteria and then you can start to overlay more aesthetic things under it and it takes on the next stage of its life and it follows into from a seed to a flower, for lack of a better term, it starts to grow and take in more environmental, programmatic, again aesthetic criteria. It's an evolution of a building as you go through the process." (personal communication, December 4, 2018)*

This suggests that a design environment, to be able to accommodate design requirements at each stage of the process, should be able to evolve as the project does. As an example, V argues that eQuest has such evolving feature that enables the designer to control more and more details as this information becomes available: "eQuest is not a very standard tool, eQuest has the capability of going in the background and changing things" (personal communication, November 10, 2018)

4.7.2. Deluge

P, providing the example of Sketchpad by Ivan Sutherland, argues that the line is reduced to its mathematical definition in many of today's digital tools:

> *"So when Sutherland developed the light pen you were talking about, he conceived of the line as a Cartesian line were as defined by its two endpoints. And so you click on the starting point and then you move the pen. It doesn't matter in what way and then you click on the endpoint." (personal communication, January 16, 2019)*

While a hand-drawn line is much more than this mathematical definition of two endpoints:

> *"the process of tracing the line is irrelevant to the two data points that actually define the line and when you trace a line with a pencil your pulse, your emotion, your thinking, the quality of the pencil, the lead, the point of it, the paper, the humidity during the day, all those things influence that complex interaction and as a result, there is so much more information to read in the pencil line that goes from A to B because it's a search, it's a gesture. It isn't only the result of two endpoints. Whereas in Sutherland's model, it's now no more than the two endpoints." (personal communication, January 16, 2019)*

P argues that a hand-drawn line provides a deluge of unintentional information which helps to stimulate the imagination:

> *"We lose so much data that we aren't able to access. As we read the drawing back to ourselves and we use it to imagine possibilities to see things we didn't intend when that we made the drawing, but that might be better than our very limited intention when we were beginning to make the line than where we end up after the line is there." (personal communication, January 16, 2019)*

4.8. Knowledge - Iteration Themes

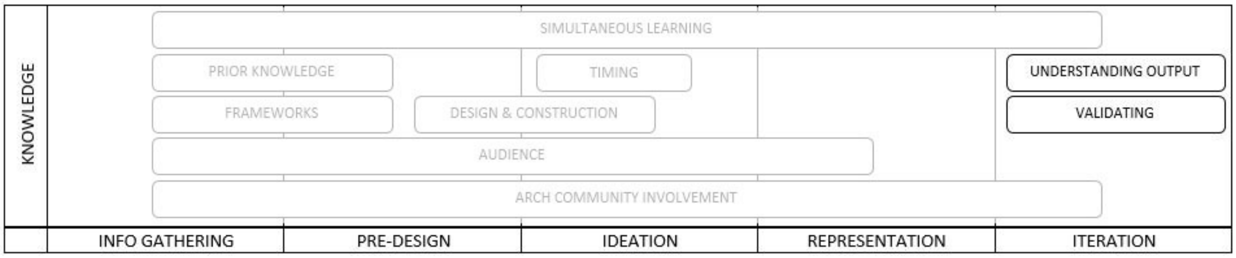


Figure 4-7 Knowledge - Iteration Themes

4.8.1. Understanding and Validating Output

Related to the *A priori Knowledge* theme, with performance analyses such as glare analysis, V raised a concern about whether architects, without going through a proper education phase, are able to understand the tools' outputs correctly and validate the results:

> *"I'm very reluctant of introducing [daylight] modeling software for architects... I'm very reluctant, because, I don't know, because especially nowadays all daylighting software come as a scripting tool, right? they don't know what is happening or they just want to pick something from, like, the internet, how do you know that that information is valid or it's giving you the right information? At least if it's a performance design consultant he's gonna think about it or if there is a lighting company or something they're gonna spend more time thinking about if they're doing the right thing but architects are not going to have time to think about it that much." (personal communication, November 10, 2018)*

Therefore, she suggests that rather than only introducing specific tools within the curriculum, it is important that students be given the necessary knowledge to understand how these tools function and how to interpret the output and validate the results. She points out that while using a performance analysis tool, architects need to "understand what is happening? what is it saying? what is the analysis saying? Is it real? Like, does it happen in real life?" (personal communication, November 10, 2018) Here, V is pointing out three required fundamental knowledge domains to use a performance analysis tool:

1. Analysis procedure (What is happening?)
2. Understanding the output (What is the analysis saying?)
3. Validating (Does it happen in real life? Can the results be believed?)

Similarly, E points out the importance of validating the results of performance analyses performed during the early stages of the design process: “Then you go to Insight and once you start using that the design is pretty much what it is so it's really just validating the work that was done in Sefaira early on”. (personal communication, December 4, 2018) In this case, they take advantage of changing their performance analysis tool from Sefaira to Insight (due to changing the modeling tool from SketchUp to Revit as the project develops) as a strategy to validate the results. This is a good example of valuable procedural knowledge architects acquire in practice.

Moreover, E mentions that as a project develops, his firm relies on consulting teams to validate the correctness of their assumptions, shaped by those performance analyses done during the early stages of the design process:

> *“we may need to stop and hand it over to the MEP team to do a real in-depth energy analysis or lighting analysis and that I don't think it changed yet I mean maybe those tools become more robust over the next 10 years but as of right now I think there's always, you do as much as you can early on to ensure that you’re not gonna be way off down the line but at some point, you do have to stop and do a more in-depth validation before you go too much further” (personal communication, December 4, 2018)*

4.9. Features - Iteration Themes

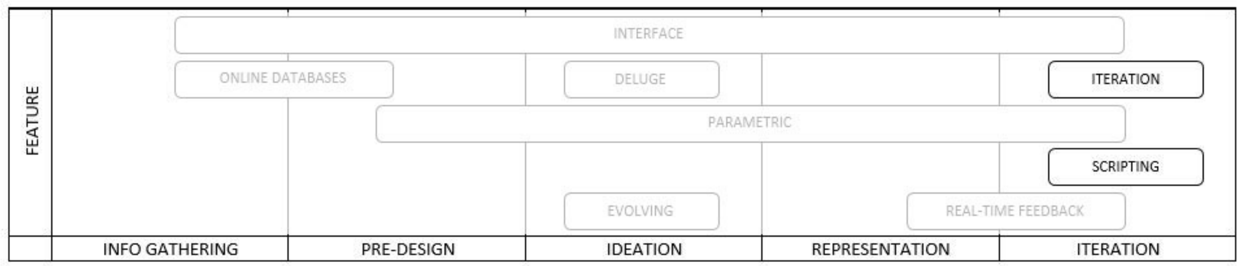


Figure 4-8 Features - Iteration Themes

4.9.1. Iteration

B, talking about his reasons for being inclined toward 3ds MAX for 3D modeling, points out that: “One of the things I really appreciate about [3ds Max] it is the animations aspect that is built into that the keyframe aspect is actually very robust and you can do a lot with animation” (personal communication, December 4, 2018) He also adds that: “the other part that I really appreciate is the rendering like the rendering software it’s super strong in terms of lighting solutions and all this.” (personal communication, December 4, 2018) He concludes that: “having it all in one package is really nice” (personal communication, December 4, 2018)

What is nice about “having it all in one package” is the smoother process for iteration. It eliminates the cumbersome process of repeating all the steps when a design change occurs.

E mentions Sefaira’s ability to facilitate iteration as its main strength for early stages of the design, during which iterations are more likely: “It’s good, the Sefaira plugin is good early on when you’re doing iterations on a design for massing and for initial fenestration design.” (personal communication, December 4, 2018)

At later stages, E points out that they consciously make an effort to facilitate iterations by using Revit's Family features: "We set up the models so that the windows can be changed kind of globally across the building at one time so that it's a pattern in a Revit family that's easy to update". (personal communication, December 4, 2018) However, he points out that the features of Insight do not intuitively facilitate iteration: "Those tools [Insight] are good for analysis but it's also to know how to set up the model to do the iterations quickly as well." (personal communication, December 4, 2018)

However, E argues that manual tools such as hand sketches and physical models are still faster for iterations:

> *"Some things require quicker iterations which would be sketches and quick little physical models and then when you kind of settle on an idea then you can go in and model it in the computer which can be a little more laborious and time-consuming." (personal communication, December 4, 2018)*

He associates this capability of manual tools with the ability to facilitate real-time feedback:

> *"It's [sketching and physical models] the easiest way to, kind of iterate through things quickly as you're getting Real-time feedback from a client, from a consultant, from anybody. Sketching things out and building little models are way faster than going back to the computer and having to sit down and start modeling geometry" (personal communication, December 4, 2018)*

For more discussion about the *real-time feedback* theme please refer to the section Real-time Feedback.

4.9.2. Scripting

Related to the *parametric* theme, V argues that scripting is the best interface to add parametric capabilities to the design environment which helps to facilitate an iterative process:

"I think scripting has feasibility for the parametric [design,] […] you have this lighter tool to change whatever you want. You have the flexibility to do what you want the model to do […] not every design is the same […] you want to be able to have the maximum flexibility to be able to do what the design is demanding. So because of that, you need scripting capabilities" (personal communication, November 10, 2018)

Similarly, E mentions that their design team is "starting to access things like Dynamo to automate processes and model more complex geometries." (E, personal communication, December 4, 2018) Here, he is arguing that scripting features help with two things:

1. to automate processes
2. model more complex geometries

4.10. Knowledge - Info Gathering/Pre-Design Themes

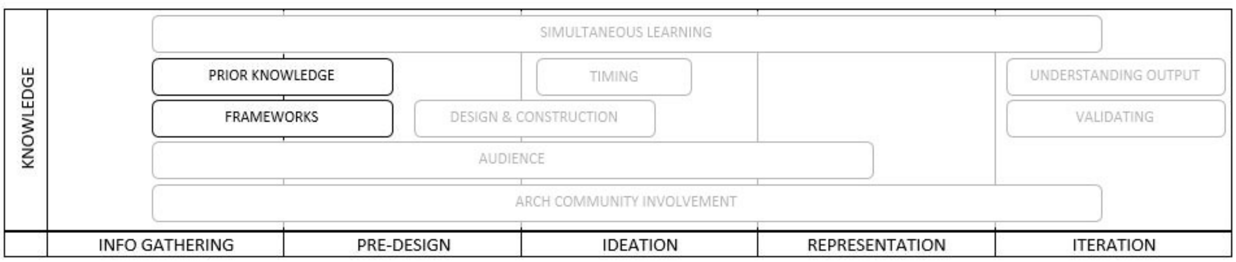


Figure 4-9 Knowledge - Info Gathering/Pre-Design Themes

4.10.1. *A Priori* Knowledge

When asked to describe her ideal working environment for designing, V replied:

"to have more information, or more understandable information on doing certain things, like, for example, I mean, now I'm thinking both like energy as well as daylighting into perspective, but how do I do a modeling for a certain thing, so my user manual has to be like the most amazing user manual." (personal communication, November 10, 2018)

When it comes to simultaneously addressing qualitative and quantitative criteria, for example view and glare, some interviewees argued that tools commonly used for performance analyses, including glare analysis, are rarely included in the curriculum in schools of architecture. For instance, V points out that “at least not in our school you don't learn anything you don't even learn energy modeling, we don't learn anything, so for example that is applicable in practical life, like, you don't learn anything [?] whatever you learn you learn it in [the] workplace.” (personal communication, November 10, 2018)

Although architects can learn these tools on their own after graduation, their use is typically not considered while preparing the curriculum. Therefore, certain necessary *a priori* knowledge can be missing from the architects’ education which can lead to very steep learning curves. For example, V argues that scripting is an important skill: “things like scripting and all that, […] I don't know, but they should include it because the next thing is all about scripting.” (personal communication, November 10, 2018) However, she mentions that not all scripting languages are similar and the decision to choose one over the others needs to be an informed decision:

> *“The simple answer is the ease of using it. Look at Python scripting, Python scripting is much easier than the scripting that is used in Dynamo. If you think about the people who are doing Dynamo, will be somebody who is like a computer coding guy” (personal communication, November 10, 2018)*

Similarly, B points out that the constellation of the tools an architect or an architecture student plans to use can require similar or different *a priori* knowledge, which can lead to a straightforward or a bumpy learning process. For instance, talking about the relationship between 3ds MAX, AutoCAD, and Rhino, he says:

> *“[3ds MAX is] removed from all of the way the other software work and so something like AutoCAD and the way you use AutoCAD is much more similar to rhino and for me, like, those two it’s just a no-brainer why you would pair all of that together, so I wouldn't force 3ds MAX on my students […] in that case,*

like the fact that I can work in AutoCAD and many of the commands are the same things that I would use in Rhino and it's just the same paradigm of like entering commands, it just makes, I think that's, that's more key to the user interface and the way we work with it." (personal communication, December 4, 2018)

This suggests that, for example, including certain *a priori* knowledge in schools' curriculum will help students to learn a group of tools more easily, AutoCAD and Rhino in this case, due to their similarities. While, for learning a different tool, 3ds MAX, schools need to incorporate another set of knowledge. A closer relationship between tool developers and academia can lead to a process that developers and schools mutually modify their products (the tool and the curriculum) based on the other party's suggestions.

4.10.2. Frameworks

E points out how a packaged bundle of information, serves as an important decision-making tool during the design process. Talking about LEED and building codes, he mentions:

"Those parameters that LEED identified as goals to get those points and credits in order to get the building certified that become benchmarks for each design that we do. […] I mean those are kind of intrinsic to design from the 60s and 70s when there were no tools like this. It was kind of more about just understanding the environment from a haptic, tactile sense and not so much of an energy or engineering criteria. But they have merged together at this point. I would say it again now that they're codified in ASHRAE and building codes" (personal communication, December 4, 2018)

Similarly, V refers to LEED as part of a knowledge framework used by architects during the design process:

"look at the LEED version 4 the IQ credits for view analysis, quality views, what that credit does? It gives you all the parameters that you can analyze view with. They have like I think 5 parameters and it says that if you satisfy 3 of these criteria you will be able to meet this credit. So, I'm pretty sure somebody has done analysis or research on these qualitative view credits, right? So nobody else is going to do spend more time on like how it is done or something so what

we do is we use these parameters and apply scripting to that as well" (personal communication, November 10, 2018)

Here, V points out the concern of misunderstanding the purpose of such knowledge frameworks. These knowledge frameworks are meant to enable the architect to go deeper by helping him/her to acquire knowledge about the basics of the topic of study. These knowledge frameworks should be used as a starting point for further studies by the architect or as a list of possibilities rather than ready-to-use recipes. The assumption that a knowledge framework is covering all aspects of a design problem and there is nothing left for the architect to study is misguided.

E suggests that Google Earth can be seen as a framework, providing certain information to the architect during the design process:

> *"So again, with SketchUp or Autodesk plugins, they all can access Google Earth imagery and Google Earth information, 3D models things like that. […] But then it takes you can use Google Earth as a starting point to model so you can kind of see what, as you are shaping the building and defining orientations and things like that, trying to focus fenestration in those areas for the people inside." (personal communication, December 4, 2018)*

Google Earth as a framework provides a graphical and easily accessible overlay of valuable information such as nearby buildings, vegetation, etc. for a qualitative study of the site. This information can also be converted to raw data for a quantitative study.

4.11. Feature - Info Gathering/Pre-Design Themes

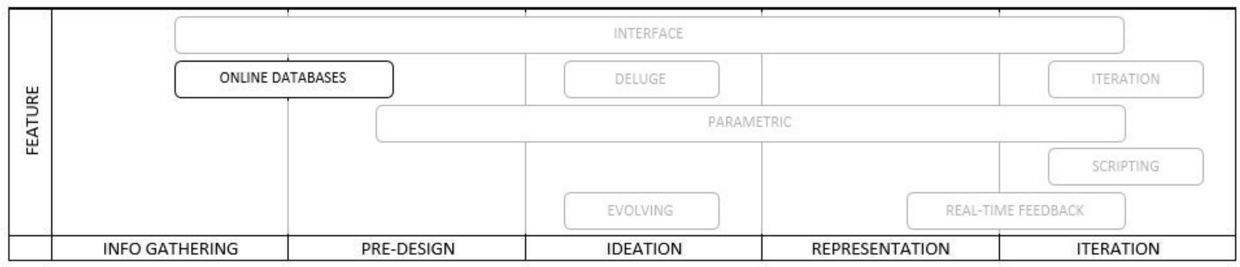


Figure 4-10 Feature - Info Gathering/Pre-Design Themes

4.11.1. Online Databases

E points out that online databases and tools such as Google Earth are becoming an integral part of many architectural software packages where in this case the software supports the qualitative study of the site:

> *"So again with SketchUp or Autodesk plugins they all can access Google Earth imagery and Google Earth information, 3D models things like that. […] But then it takes you can use Google Earth as a starting point to model so you can kind of see what, as you are shaping the building and defining orientations and things like that, trying to focus fenestration in those areas for the people inside." (personal communication, December 4, 2018)*

This suggests that these online databases and tools are supporting decision-making for architects (please refer to section Frameworks).

4.12. Knowledge - Pre-Design/Ideation Themes

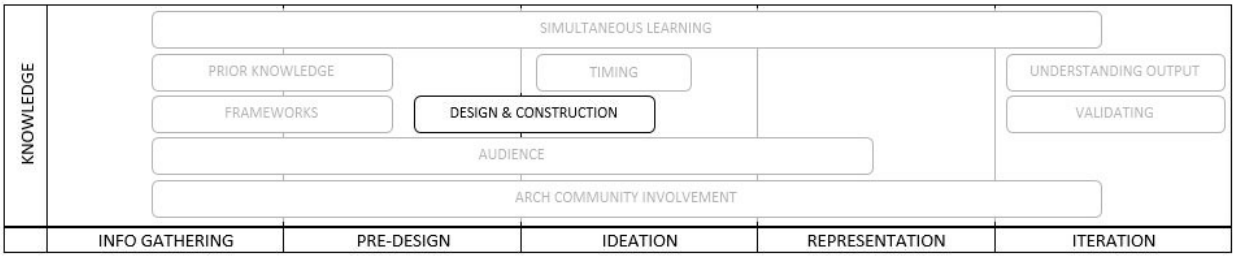


Figure 4-11 Knowledge - Pre-Design/Ideation Themes

4.12.1. Relationships between Design and Construction Tools

P argues that the close relationships between construction tools and manual tools used by architects (for instance the evolution of masons' square to architects' triangle) helped architects to internalize certain knowledge about construction in an intuitive manner:

> *"So, the architects' original drawing tools come from the construction site. The T-square of the drawing board for making horizontal lines comes from the carpenter square for making marks on lumber to show where to cut the lumber. What in the United States we call the triangle and in Europe, they call the set-square, comes from the Mason square which was used to mark the block of stone to indicate where, where to carve the stone so these tools were very much a part of the construction site, the plumb line and all that, it all comes right out of the construction site. So when architects left the construction site, the natural model for them to use is how you laid out the building on-site you now lay it out on the drawing. So the drawing sheet became the building site and the architect miniaturized everything that was happening on the site so that it could happen on the drawing sheet so there was a natural connection between practices in building buildings and building drawings and that analogous relationship was a very strong and was remained as intuitive knowledge throughout the centuries." (personal communication, January 16, 2019)*

This is similar to Williams and Tsien (both practicing architects) argument: "Our desire to continue to use the tools of the hand, even as we may begin to use the computer, has to do with their connection to our bodies. Buildings are still constructed with hands, and it seems that the hand still knows best what the hand is capable of doing." (1999)

4.13. Cognition - Pre-Design/Ideation Themes

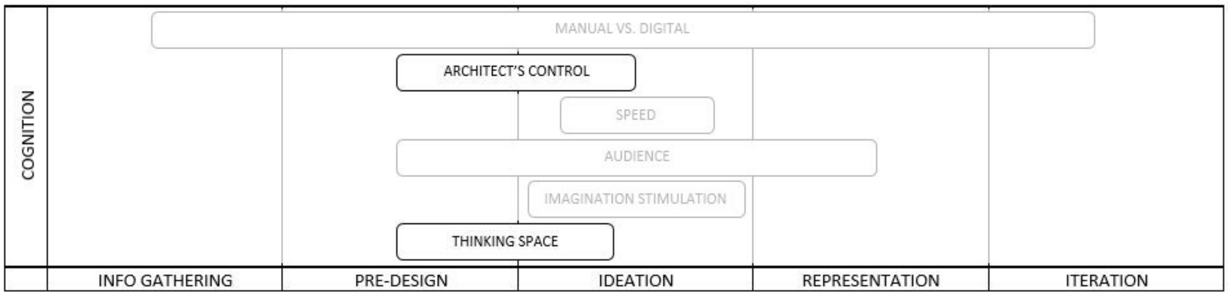


Figure 4-12 Cognition - Pre-Design/Ideation Themes

4.13.1. Thinking Space

Related to the *Imagination Stimulation* theme, when describing her ideal working environment, V mentions that, while using a tool, she likes to spend more time on design thinking compared to the time she spends on 3D model manipulation:

> *"I would like to spend less time on the modeling then I would like to spend more time on like building the system or building the you know or experimenting on the design aspect like changing or comparing the different parameters instead of spending time in the actual model building process and prepare the geometry process" (personal communication, November 10, 2018)*

This suggests that tools are characteristically different in their ability to create a thinking space. As discussed in the literature review, certain 3D model manipulation tasks may divert the architect's mind from engaging with the design problem.

4.13.2. Architect's Control

As discussed in the literature review, the architect needs to feel in control of the tool and some new digital tools do not address this need. P argues:

> *"I think it's very important if you are only a user you're limited by the limitations of the tool, but if you can go in and adapt the program to do other things you want to do, it gives you much more ability to take control of the situation and work with it at a higher level." (personal communication, January 16, 2019)*

This lack of control is illustrated in E's description of Revit's limitations:

> *"Revit has limitations as what it would let you model but that's because they define some parameters within it because they made an effort to set those parameters somewhat is really buildable. So, you can model, if you go to 3DS Max or any of these other computer animation software, you can model all kinds of stuff but you still have to take that through a translated, translational process to another software to turn it into something that can actually be documented and built or Revit is trying to do that for you. So in those respects it's, you can say it's limiting but in a good way." (personal communication, December 4, 2018)*

4.14. Characteristic - Pre-Design/Ideation Themes

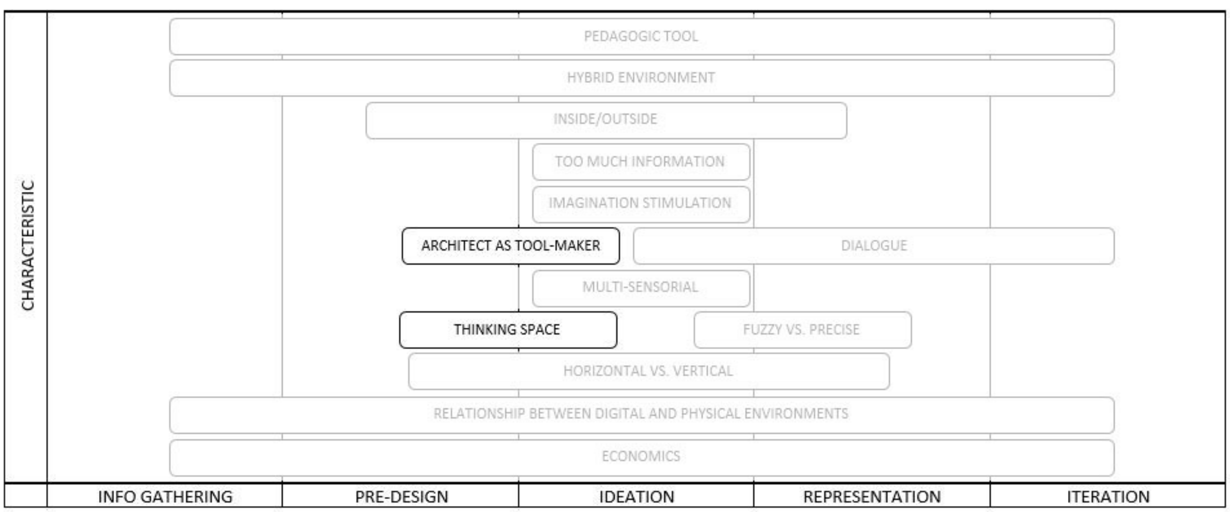


Figure 4-13 Characteristic - Pre-Design/Ideation Themes

4.14.1. Thinking Space

Comparing digital tools such as modeling on a computer with hand sketching and physical models during the early stages of the design, E argues that: "They're just, they're not as (pauses to think) fluid and as intuitive as just sitting down and talking out ideas and sketching as you're going." (personal communication, December 4, 2018) P argues that certain characteristics in some manual tools (their multi-sensorial characteristic here) supports creating a thinking space:

> *"So, there is a strong multi-sensorial relationship between the activities of the traditional drawing and building and so when we use these tools, like when you sharpen a cedar pencil you get the smell of wood. So all of these things suggest architectural thinking that is very strongly linked to the multi-sensorial nature of the building site of experiencing environments in the built world, and so the ways that architectural drawing help to reinforce that aided the architects' imagination." (personal communication, January 16, 2019)*

Explaining in more details, P argues that through a historical shift in our perception of the role of the architecture drawings (from active spaces of thinking to mere vehicles to transfer information), the development of this characteristic has been overlooked in digital tools:

> *"in general I think what happened historically is that in the Enlightenment when the idea of the rational mind was dominant through Descartes we rationalized architectural drawing so that we understood it as something that is a record of the mind's thought, rather than being an active space of creation and thinking and so once we attend to architectural drawing as a part of thinking rather than information transfer, then I think it opens up tremendous opportunities for how we could continue to develop electronic tools to make them really work for architects" (personal communication, January 16, 2019)*

Providing an example, P argues that a disconnection between various senses of the architect using certain digital tools results in a distance and disengagement between the design and the designer, which is detrimental in the creation of a thinking space:

> *"the way we move the mouse in order to make a drawing on the computer has nothing to do with where the lines are on the computer. So if you trace the movements of the mouse. It has nothing to do with the information that were generating so the physical activity of the hand and arm are entirely unrelated to the visual information and of course, that makes one feel more distant from the output and it's harder to stay engaged, right? So it leads to boredom on the job, lack of satisfaction and it doesn't automatically bring us back into how we think about building the line as a wall" (personal communication, January 16, 2019)*

4.14.2. Architect as Toolmaker and Design Environment Coordinator

As discussed in the literature review, Davis and Peters argue that through a plug-in based ecosystem in design software "The coordination and creation of the design environment is itself becoming the domain of the designer." (2013) Similarly, B advocates for a design environment that consists of "tools you put together in order to see the project through a certain lens and work through a series of design problems." (personal communication, December 4, 2018) He argues that the root of the problem is the absence of the architectural community in the development process of these tools:

> *"I believed that the problem quite honestly is the fact that we're not the one driving the tool-making. We're too content to sit back and just say like what's the new thing coming to us and then we use it and we complain that it doesn't really do what we want." (personal communication, December 4, 2018)*

P too argues that it is only by transcending the role of a mere user, that architects can realize the full possibilities of new digital tools:

> *"I think it's very important if you are only a user you're limited by the limitations of the tool, but if you can go in and adapt the program to do other things you want to do, it gives you much more ability to take control of the situation and work with it at a higher level." (personal communication, January 16, 2019)*

4.15. Characteristic - Ideation/Representation Themes

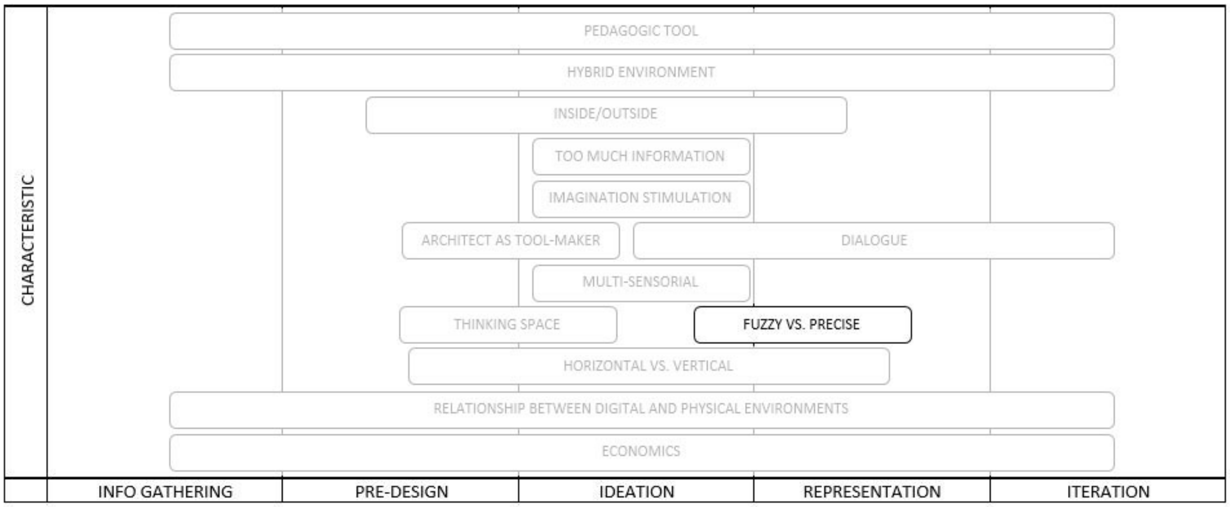


Figure 4-14 Characteristic - Ideation/Representation Themes

4.15.1. Fuzzy versus Precise

"Certainty is a prison." Write Williams and Tsien (1999) in their essay on slowness. E illustrates this prison in more details:

> *"in some respects having kind of the computer can seem too real and too final to people when the information being displayed is still, in essence, a sketch, if that makes any sense, so being able to keep things fuzzy at the right times whether through hand drawings or little physical models is valuable so you don't get bogged down and things you not necessarily ready or willing to discuss at that stage of the project." (personal communication, December 4, 2018)*

Similarly, J argues that current digital tools are not ambiguous enough for the early stages of the design process:

> *"as soon as you draw a dot you are limiting the infinity, and as you keep drawing you are limiting more […] the digital at least now, does not have feeling and you need to project that into it, while with a hand-drawn sketch the feeling is there. […] it has something to do with ambiguity, you know, ambiguity is a good thing. Computers are precise, they can be ambiguous, but they are not. […] to have a paradigm you need paradoxes, enigmas, and conundrums. Good*

architecture is dealing with these." (personal communication, November 2, 2018)

Williams and Tsien believe that these clear and final images of the building close down the process of questioning:

> *"For us, elevations are always the last part of a building to be developed. Often, we are at the end of design development before we even begin to rough out the elevations. This is because elevation drawings close down the process of questioning by making the image of the building too clear, too "graspable," and therefore too final." (1999)*

E has a similar observation and points out a similar danger of precise drawings at the early stages of the design process:

> *"We have the experience where you do too much on the computer too early on because the tools are so robust and it's quick to do a quick little building in SketchUp and put it in Lumion and have these renderings that look like oh the building is already done and designed when really that's still conceptual sketch" (personal communication, December 4, 2018)*

Moreover, Williams and Tsien argue that avoiding cleanness is essential in developing a sense of wholeness during the design process:

> *"And if every time a change is made, a new printout is made, there is the problem that the printouts are too clean. They don't show the scrubbed and messy sections of erasure, so there is no evidence to indicate the history of the development of an idea. Crucial to creating wholeness is the understanding of the development of the idea." (1999)*

P argues that the root of this problem is in misunderstanding the role of architectural drawings:

> *"I think the fundamental mistake occurs and I believe this is where you are going with your question of the fundamental mistake is to assume that architectural drawing is to illustrate the future building as if it's a picture of the future building. But what it really is, is a… so people mistake architectural drawing is being an illustration of the future building as if it's a photograph of the future, and so they try to make it as realistic as possible and super-realism actually gets*

in the way of a lot of productive architectural work because it restricts the role of the narrative of architecture." (personal communication, January 16, 2019)

Similarly, P believes that super-realism is restrictive. He describes this narrative role of architecture by pointing out that:

"When architects are presenting a project, they are telling a story and they use the drawings like in a fairytale book to help people to imagine, but not to tell you exactly what the witch's house on Hansel and Gretel looked like so you can imagine a house made of candies and cookies. But it's really difficult to show literally a house made of candies and cookies and that difference is important because it maintains an openness that is required in the complex activity of designing and building so that there is the opportunity to continue to develop a design all the way through construction so that it can respond to all the complex problems that we encounter with building and if you're trapped on a… if you're trapped having to, to create a certain picture from the design phase for a building than it actually hurts the ability to develop the architecture through the process of designing and building" (personal communication, January 16, 2019)

Here, P is advocating for an openness that is not limited to the early stages of the design process but in fact, extends to the end of construction of the building. He argues that this openness is achievable through maintaining ambiguity or fuzziness in the process:

"in the sense that an architect can put many different lead points on a pencil to create different kinds of lines, we should be able to do that with computers too. So the more it's been pretty organized, like with BIM the less there is an opportunity for architectural imagination and the more it's about producing rather than imagining." (personal communication, January 16, 2019)

4.16. Feature - Representation/Iteration Themes

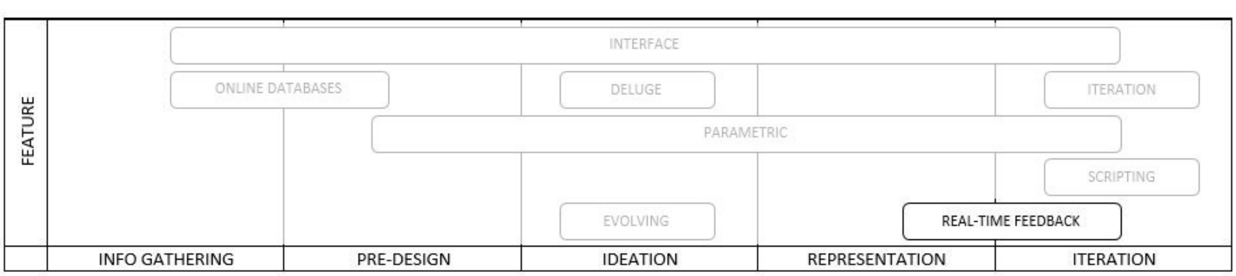


Figure 4-15 Feature - Representation/Iteration Themes

4.16.1. Real-time Feedback

As discussed in the *iteration* theme section, E argues that one feature in hand sketches and physical models that facilitates the iteration process is the space they create for real-time feedback:

> *"It's [sketching and physical models] the easiest way to, kind of iterate through things quickly as you're getting Real-time feedback from a client, from a consultant, from anybody. Sketching things out and building little models are way faster than going back to the computer and having to sit down and start modeling geometry" (personal communication, December 4, 2018)*

B approaches the same concept but through experimenting with new digital tools and through a different perspective:

> *"A lot of those tools [Arduino] are really basic right now but this idea that we can sense the environment, take that data and process it and then affect the environment and then we sense it and do it all over again. It's a big paradigm shift that it's happening in real-time." (personal communication, December 4, 2018)*

B mentions that attention to this real-time process raises questions about the kind of tools that would facilitate it:

> *"so, the labs that I have been working at and creating have been all about that real-time interface with the physical world and what are the tools we need to make that happen. The ideal version of that is one that is near real-time and we're getting all the data we want and we're able to kind of instantly affect the physical world that we're working at." (personal communication, December 4, 2018)*

He argues that through simultaneously utilizing several media to understand, represent, and eventually modify the design, one can bridge the qualitative and quantitative aspects:

> *"a lot of the ways we represented that was through the films we were creating side-by-side with the point cloud models and the real-time analysis of that and then tying together those two so that we can understand the qualitative or aesthetic piece directly in relation to all of the data that's coming off of that." (personal communication, December 4, 2018)*

B mentions Grasshopper as a tool that through its visual scripting interface, facilitates this process of real-time feedback:

> *"some of the ways we taught grasshopper has been to show students that we can use grasshopper to get a, to add this analytical overlay, it's not really fast enough yet but you can have real-time contouring, real-time shading of slope or things like this." (personal communication, December 4, 2018)*

Similarly, B points out that in "software like 3ds MAX, we're no longer hitting the render button but we're just modeling and we're getting the kind of, the final render." (personal communication, December 4, 2018) In other words, by eliminating the need to push a button for rendering and getting the result in a separate window, thanks to the higher processing powers of new computers, the architect is able to get the feedback of a rendering in real-time. He mentions that similar feedbacks are becoming accessible in real-time for architects: "we're able to essentially interactively understand cut-and-fill, slope, and aspect, and all of these things as we're modeling." (personal communication, December 4, 2018)

B argues that these real-time feedbacks can be further developed through ideas such as the application of virtual reality and augmented reality technologies:

> *"creating like a real-time first-person interface that not only takes like the models they are making in the lab but then allows you to occupy them walk through them with the analytical information in them." (personal communication, December 4, 2018)*

4.17. Cognition - Pre-Design/Ideation/Representation Themes

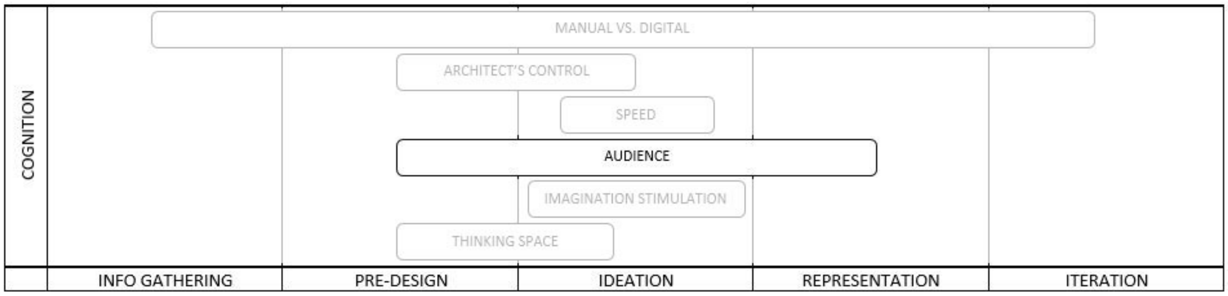


Figure 4-16 Cognition - Pre-Design/Ideation/Representation Themes

4.17.1. Audience

V points out that the differences between various audiences when viewing the output from a tool are not limited to their knowledge. Each person, even those with similar educational backgrounds, might utilize tools in a slightly different manner:

> *"think about who is your person, you don't compare an architect and a performance design consultant together because their requirements are completely different. There might be architects but even in architects, there are different areas like in a studio you might have a design architect, you might have a person who is specifically doing this analysis and everything but does he have the sufficient information like it's like so complex like I don't know, you have to think about it that way, an architect not everyone will be doing an analysis, they might not be interested" (V, personal communication, November 10, 2018)*

4.18. Characteristic - Pre-Design/Ideation/Representation Themes

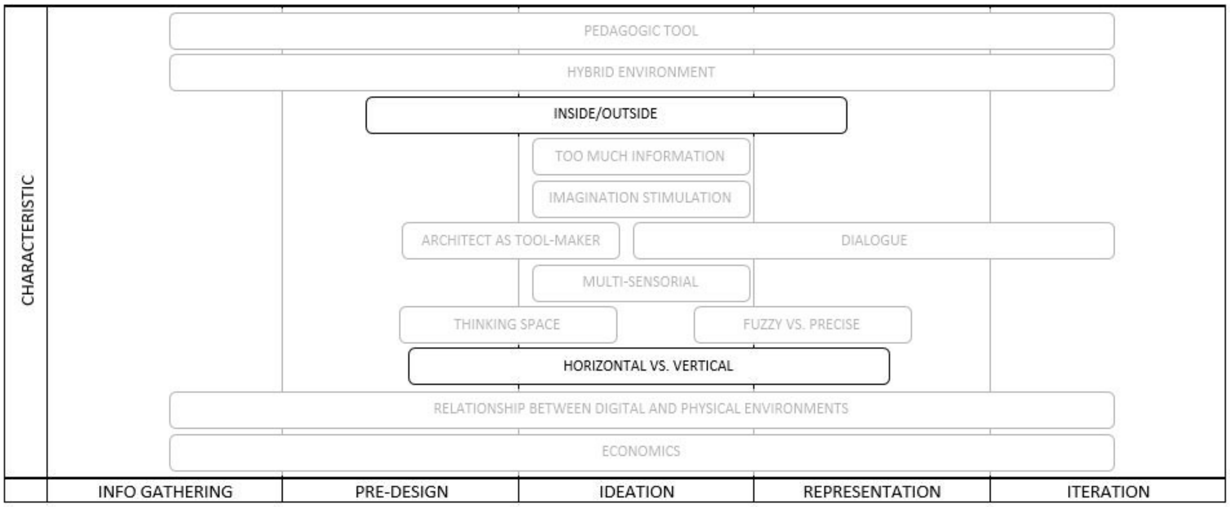


Figure 4-17 Characteristic - Pre-Design/Ideation/Representation Themes

4.18.1. Inside/Outside

Related to the *hybrid environment* theme, E argues that there is an interconnected inside/outside relationship during the design process which is not linear (designing the outside first for example, and then moving to the inside) but rather involves moves from one to the other:

> *"There is an inside-outside design process there is the massing and what the building is but then there is also the program that's inside the building that starts to influence where windows and things go so it's kind of a back and forth that's never one or the other or you do everything outside and then go inside." (personal communication, December 4, 2018)*

This suggests that the concept of a hybrid design environment might be an important characteristic for facilitating this process during the design process.

4.18.2. Horizontal versus Vertical

P points out the difference between working on a horizontal surface such as a drawing table versus working on a vertical surface such as a monitor:

> *"the way the architects drawing table is fundamentally horizontal, with a slight tilt to orient it to the body of the drafter and that that connects you to a way of thinking about constructing, of building up and in the computer the screen is almost always vertical and we call it Windows and all that and so that is a process of looking at something" (personal communication, January 16, 2019)*

Providing a historic background of this difference, P mentions:

> *"artists were imitating the view in the countryside so the vertical easels, Alberti already described in the Renaissance as being a window so you're re-creating the view from a distance, whereas the architect is working on a field on the site and constructing. So those are fundamentally different experiences that can be overcome." (personal communication, January 16, 2019)*

Pointing out the cognitive consequences of each, P argues:

> *"It isn't that we couldn't work with vertical screens and, and conceive of it as a construction but there's a tendency to approach it as when you're looking at a screen to see it see within the screen as if it's an object in the distance as if it's Alberti's window looking into the world so it tends to move us away from the object we're designing and attends to objectify it like a painting rather than a constructive activity like the horizontal tradition of the drawing table." (personal communication, January 16, 2019)*

P argues that the dominance of vertical monitor surfaces over horizontal drawing table surfaces has had a major influence over contemporary architects' esthetics:

> *"that's just one example of the many ways that people haven't really been thinking about how the tools influence our relationship and I would argue that the interest in complex curving surfaces is in part the result of this viewing an object at a distance on the screen so that it, it lacks a spatiality because we are not engaging with it as a space we're engaging with it as an object at a distance." (personal communication, January 16, 2019)*

4.19. Characteristic - Ideation/Representation/Iteration Themes

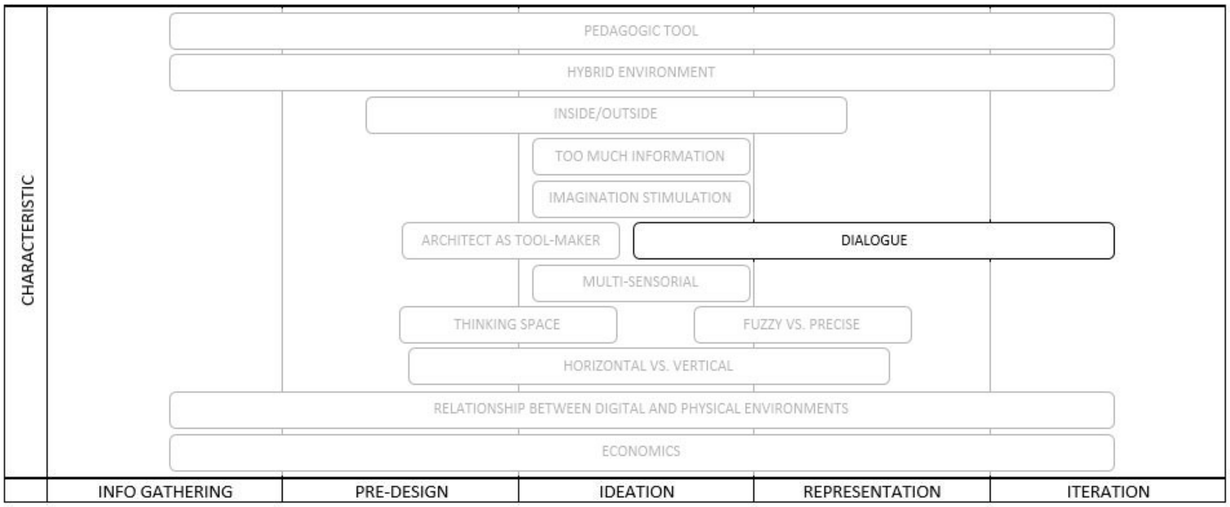


Figure 4-18 Characteristic - Ideation/Representation/Iteration Themes

4.19.1. Dialogue

Williams and Tsien argue that one benefit of a sketchbook (consisting of all the hand sketches done for a project by various people in the design team) is its ability to facilitate a simultaneous process of collective ideation: “There are several reasons why the sketchbook is useful. It allows several people to work on parts of a specific section at the same time.” (1999) E points out this ability of hand sketches and associates this ability to the dialogue characteristic of sketching as a tool:

> *“I think that’s [sketching and physical models] the easiest way to communicate initial ideas. I mean verbally is, everybody got their own language and the only way to describe what they’re seeing in their head but if you can kind of sketch it up and draw it, that’s the only way to get an image out of your head and into somebody else’s head. […] It's more of a dialogue or conversational tool, conversational process where you know if we were having a conversation there is a client here and we were talking about ideas.” (personal communication, December 4, 2018)*

When it comes to performance analysis, E believes that this dialogue between the design team and the MEP team is an important and unavoidable process:

> *"we may need to stop and hand it over to the MEP team to do a real in-depth energy analysis or lighting analysis and that I don't think it changed yet I mean maybe those tools become more robust over the next 10 years but as of right now I think there's always, you do as much as you can early on to ensure that you're not gonna be way off down the line but at some point, you do have to stop and do a more in-depth validation before you go too much further" (personal communication, December 4, 2018)*

However, he believes that the full possibilities of new digital tools to facilitate this dialogue has not been actualized yet:

> *"The power of that tool [Revit] is most actualized when everybody has their own model and it's all hooked back to the central, but there certainly are limitations for civil engineers and Autodesk is trying to fix that stuff and landscape as well cause they, still kind of, live in a 2D world for drawing and sketching so a lot of the times we have to take their drawings and their information and model it out for them which can be a problem from a contractual and compensation standpoint because you're doing somebody else's work. Engineering wise it could be the same thing, if they only draw their stuff in 2D you lose the power to being able to do class detection and do real coordination between MEP systems and structural and architectural design." (personal communication, December 4, 2018)*

E argues that this problem is partly due to the lack of a common language. He believes that a more graphical language can facilitate the dialogue between various parties involved in a project:

> *"they communicate as engineers, so they are sending graphs and other things back and that's not always the easiest stuff for people who are not used to reading that information to understand. So having an easy to understand graphic language is always helpful and we'll sometimes take their stuff and kind of play with how the quantitative data is communicated visually to clients or other people." (personal communication, December 4, 2018)*

V has a similar view. She believes that an ideal design environment can facilitate this dialogue by providing each party with insights from others and help each party to better understand others' views and concerns:

“but not everyone does the same job like a mechanical engineer will not fit into a daylight model and he doesn't even understand all the aspects similarly a performance design specialist may not know everything about systems everything about the design you know so it's like a lagging aspect and I would like to get some information from either side you know like as in I would like to get some messages saying that if like done some model this is a very ideal situation it would not happen like I would like to get some error messages or warning messages in those terms also this is like extremely ideal building will never perform this way” (personal communication, November 10, 2018)

Similarly, P points out the role of architectural drawings as a tool to facilitate a dialogue between various parties involved in the project:

“When architects are presenting a project, they are telling a story and they use the drawings like in a fairytale book to help people to imagine, but not to tell you exactly what the witch's house on Hansel and Gretel looked like so you can imagine a house made of candies and cookies. But it's really difficult to show literally a house made of candies and cookies and that difference is important because it maintains an openness of the, is required in the complex activity of designing and building so that there is the opportunity to continue to develop a design all the way through construction so that it can respond to all the complex problems that we encounter with building and if you're trapped on a… if you're trapped having to, to create a certain picture from the design phase for a building than it actually hurts the ability to develop the architecture through the process of designing and building” (personal communication, January 16, 2019)

4.20. Knowledge - Info Gathering/Pre-Design/Ideation/Representation Themes

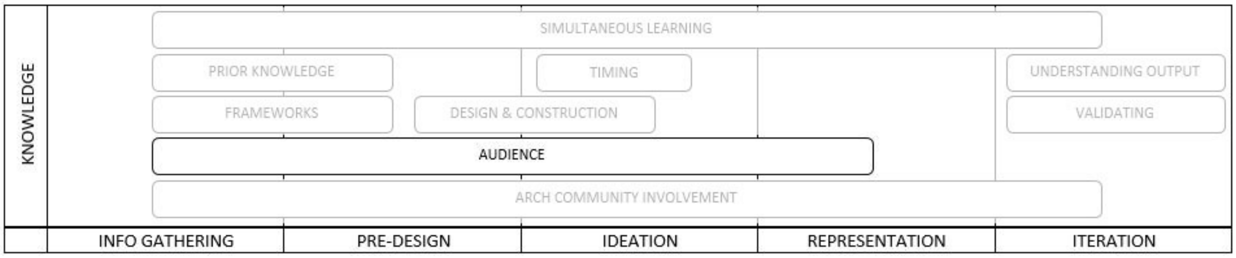


Figure 4-19 Knowledge - Info Gathering/Pre-Design/Ideation/Representation Themes

4.20.1. Audience

P points out the need to consider different audiences when producing architectural drawings:

> *"So there are many different audiences for architectural drawing and it helps to be clear what audience you're dealing with. So when we talk about this question [the possibilities of VR and AR tools], we tend to think more about the client or the potential inhabitants of the building as the audience, whereas what I was talking about before, it was more drawings for architects that help them to think through the design." (personal communication, January 16, 2019)*

Each audience group has a different knowledge set that informs his/her interaction with the design. This suggests that tools with similar objectives should have different characteristics depending on their target audience. For instance, Autodesk's AutoCAD Architecture, Mechanical, Electrical, etc. versions try to address different audiences of a CAD drafting environment.

V mentions the same idea but goes further by pointing out to even personal preferences within each audience group which makes it hard to generalize the needs and expectations within each group:

> *"think about who is your person, you don't compare an architect and a performance design consultant together because their requirements are completely different. There might be architects but even in architects, there are different areas like in a studio you might have a design architect, you might have a person who is specifically doing this analysis and everything but does he have the sufficient information like it's like so complex like I don't know, you have to think about it that way, an architect not everyone will be doing an analysis, they might not be interested" (personal communication, November 10, 2018)*

B discusses the same concept as P but more from the perspective of the tools that architects use and the two roles they can have (representation and imagination simulation):

> *"for me, there are two aspects to the tools we use in design. One of them is I would say more about representation. So it's about, it's about taking a design speculation, a proposal and, and building a package of drawings, documents, movies so that we can talk about that with people outside of us and our design*

team. And sometimes it's for designing but mostly it's for like an external audience. And so a lot of what we do is that in my opinion, it is about making drawings, making animations, making presentations to talk about our work. Internally, I think it becomes much more personal, it's about the design team or about you as a designer and the tools you put together in order to see the project through a certain lens and work through a series of design problems" (personal communication, December 4, 2018)

E mentions that how an easy-to-understand "graphic language" can play an important role in communication between various audience groups involved in a project:

"they communicate as engineers, so they are sending graphs and other things back and that's not always the easiest stuff for people who are not used to reading that information to understand. So having an easy to understand graphic language is always helpful and we'll sometimes take their stuff and kind of play with how the quantitative data is communicated visually to clients or other people." (personal communication, December 4, 2018)

V mentions that how in their case, Revit is used as a centralized database to communicate information between various groups involved in the project:

"Revit also not really like [for] modeling purposes but mainly to get the information like of the structure or something like that get that and then translate it into another software or model or something. We used to use Revit for just that purpose like getting the data from Revit into like whatever like Rhino or IES or AutoCAD or whatever." (personal communication, November 10, 2018)

E points out that the facilitation of the dialogue between various parties in the design project in some cases requires a specific person (project manager) within the design team:

"that's maybe the unsexy side of the design process but that's the project management side of it as well so it's understanding budget, constraints, code requirements, aesthetic desires of the people in the firm the clients you know aesthetic desires, and their expectations. It's a learning process for everybody and it's keeping everybody educated on what the main, and getting by on what the main goals are for the design and for the project throughout the process." (E, personal communication, December 4, 2018)

4.21. Feature - Pre-Design/Ideation/Representation/Iteration Themes

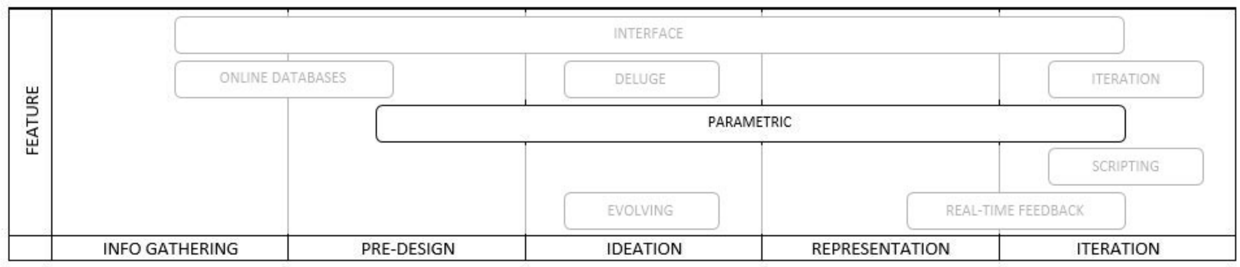


Figure 4-20 Feature - Pre-Design/Ideation/Representation/Iteration Themes

4.21.1. Parametric

Related to the *Iteration* theme, V believes that parametric features in tools facilitate the iteration process:

> *"you have to go back and forth with the architect as in what kind of window is there? how many windows have this U-value or R-value? […] how tall is, like exact information, it takes time and what happens is when you are doing it in your early design phases most of the time by the time you are done with analysis they change their design and then again you have to, you spend more time, and you know, there are no parametric capabilities" (personal communication, November 10, 2018)*

Here, she suggests that parametric features help to address two problems that raise the need for iteration:

1. When the design changes
2. When the information is not available at that stage

4.22. Knowledge - All Stages Themes

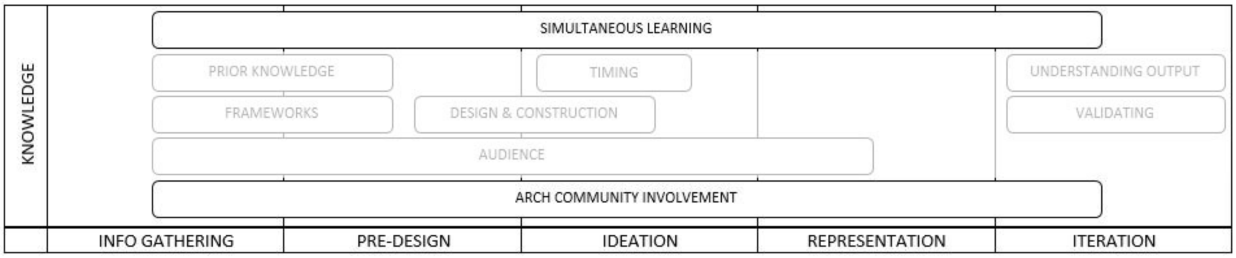


Figure 4-21 Knowledge - All Stages Themes

4.22.1. Simultaneous Learning

As B argues: “The leap [from manual tools to digital tools] has happened so quickly, it’s difficult to teach students how to think with the digital tools.” (personal communication, December 4, 2018) This suggests that there has been a difference between the way architecture students learn digital tools versus how they learn manual tools in the curricula of many architecture schools. Historically, students learn the manual tools as they are learning how to design. For example, many of the exercises that students perform in the first few years of their education simultaneously address a design skill and technique, where technique often includes the proper utilization of the tool. Naturally, as students advance, the exercises become less about technique and more about design skills. However, often around this same time, students start using digital tools and it seems that this simultaneous learning process is not as effective for digital tools.

As a consequence, the lack of simultaneity between skill and technique can lead to digital tools being forced to emulate how analog tools are used: “digital tools have been introduced and really the only way we knew how to use those digital tools was the same way we had used the analog tools.” (B, personal communication, December 4, 2018)

4.22.2. Architecture Community Involvement

P, similar to (Cross, 2006) as discussed in the literature review, argues that there seems to be a gap between the needs of the designer and the functioning of the digital tools:

> *"even if a computer programmer were to talk to architects, they wouldn't hear a lot of those things, they would hear the rationalized explanations that developed in the Enlightenment and so because we didn't articulate those important relationships about architecture, no one else could be expected to be aware of them. So from my point of view, it was a loss of translation over time, that led to that." (personal communication, January 16, 2019)*

As a result, he argues for the more active involvement of the architecture community in the development of the tools:

> *"I think it's very important if you are only a user you're limited by the limitations of the tool, but if you can go in and adapt the program to do other things you want to do, it gives you much more ability to take control of the situation and work with it at a higher level." (personal communication, January 16, 2019)*

4.23. Cognition - All Stages Themes

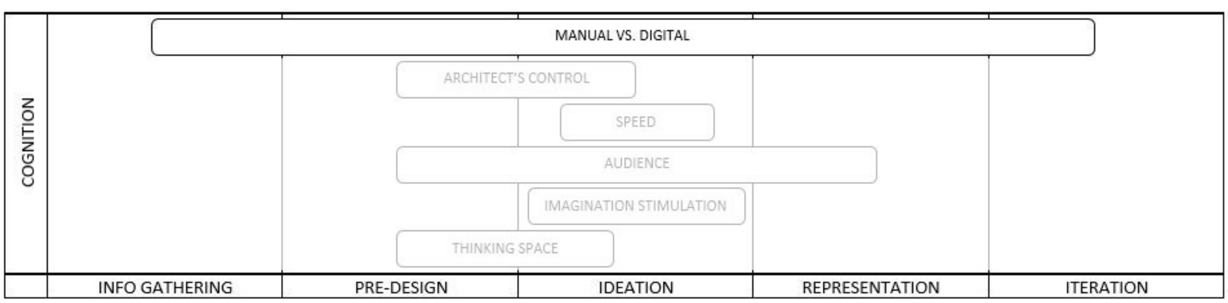


Figure 4-22 Cognition - All Stages Themes

4.23.1. Manual versus Digital Differences

B points out the differences between manual and digital tools while mentioning that without studying these differences we are not able to assign value to them:

> *“I think there are differences I don't doubt that if I got a piece of paper and start working with it and you and I are like making a form, that there is something slightly different about that than there is about you and I interacting together on a computer. Right? but I don't qualitatively believe this is better than this.” (personal communication, December 4, 2018)*

P provides an example of such differences that require an in-depth cognitive study:

> *“the way we move the mouse in order to make a drawing on the computer has nothing to do with where the lines are on the computer. So, if you trace the movements of the mouse. It has nothing to do with the information that were generating so the physical activity of the hand and arm are entirely unrelated to the visual information and of course, that makes one feel more distant from the output and it's harder to stay engaged, right? So it leads to boredom on the job, lack of satisfaction and it doesn't automatically bring us back into how we think about building the line as a wall” (personal communication, January 16, 2019)*

B argues that both manual and digital tools have strengths and weaknesses and one group alone cannot incorporate all that these tools have to offer (for example correcting mistakes in a digital 3D model is usually easier than in a physical model, however, design mistakes are usually more evident in physical models since components in a physical model follow the same physical laws as the components in the building):

> *“There is a difference and we’re losing something with one and losing something with the other or we are gaining something with one and you know what I mean but it's neither here nor there at the end of the day.” (B, personal communication, December 4, 2018)*

This suggests that an ideal working environment cannot be exclusively manual or digital. This idea is further discussed through the *hybrid environment* theme.

4.24. Characteristic - All Stages Themes

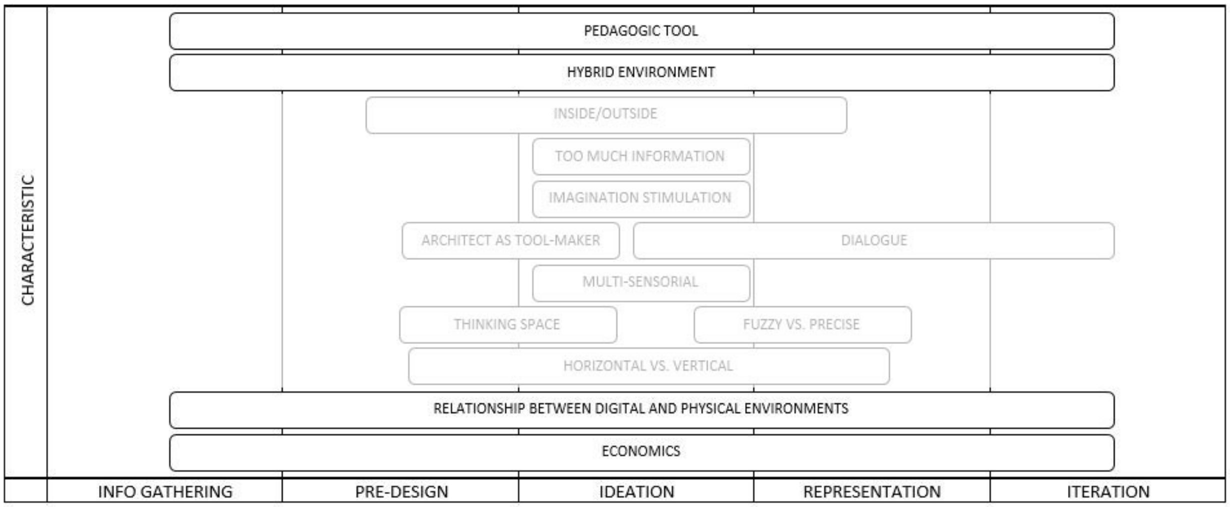


Figure 4-23 Characteristic - All Stages Themes

4.24.1. Pedagogic Tool

While describing her ideal working environment (digital, manual, or a combination of both), V mentions that she would like to have tools that provide more information on how to utilize that tool:

> *"to have more information or more understandable information on doing certain things like for example I mean now I'm thinking both like energy as well as daylighting into perspective but how do I do a modeling for a certain thing so my user manual has to be like the most amazing user manual" (personal communication, November 10, 2018)*

When asked how does she think this information should be presented to her as the user, V argues: "it can explain it in terms of a video or in terms of more graphical representation of explaining things that would be amazing" (personal communication, November 10, 2018)

4.24.2. Hybrid Environment

B, pointing out the benefits and shortcomings of both manual and digital tools, argues that neither of those alone is the answer, suggesting that a combination of these two sets of tools is desirable:

> *"There is a difference and we're losing something with one and losing something with the other or we are gaining something with one and you know what I mean but it's neither here nor there at the end of the day." (personal communication, December 4, 2018)*

He provides an example of such a hybrid environment, inside which, the architect combines various media to study the design problem from a unique perspective:

> *"a lot of the ways we represented that was through the films we were creating side-by-side with the point cloud models and the real-time analysis of that and then tying together those two so that we can understand the qualitative or aesthetic piece directly in relation to all of the data that's coming off of that." (personal communication, December 4, 2018)*

B argues that blurring the boundary between the physical and digital environment is another approach to creating such hybrid environments for design:

> *"There is this kind of spot we're at though that we are… how do I say this, Our move from the way we're working in the computer and then transferring that to some sort of fabrication and then back into the computer again that, that, that step is one that I think needs the most work for landscape architects and so that that process between or the process between what's digital and what's physical and how we move between those two spaces is the one where I think creating that kind of ideal space to instantly affect the physical world" (personal communication, December 4, 2018)*

E provides a similar argument, pointing out the possibilities of virtual and augmented reality tools as well as 3D printing:

> *"I haven't dabbled into virtual reality and augmented reality tools and I would be interested to see how that could kind of maybe bridge the two worlds in some ways that would probably be the next thing to start play with and test out. We do prototyping and 3D printing and we've done laser cutting and those tools are*

evolving as well. But I think maybe that idea that you can kind of be in a virtual environment, playing with something like it is clay and then sending it out to a 3D printer I think that would be interesting if it was quick again and iterative and not a time-consuming process." (personal communication, December 4, 2018)

In his argument in favor of hybrid environments, E provides two criteria for such design environments:

1. Quick
2. Iterative

4.24.3. Relationship between Digital and Physical Environments

B explains that new digital tools are providing new opportunities to bridge the physical and digital worlds in real-time and let these two worlds mutually affect one another:

> *"so, the labs that I have been working at and creating have been all about that real-time interface with the physical world and what are the tools we need to make that happen. The ideal version of that is one that is near real-time and we're getting all the data we want and we're able to kind of instantly affect the physical world that we're working at." (personal communication, December 4, 2018)*

Similar to the discussion about the *hybrid environment* theme, B argues that this approach blurs the boundary between what is physical and what is digital:

> *"Our move from the way we're working in the computer and then transferring that to some sort of fabrication and then back into the computer again that step is one that I think needs the most work for landscape architects and so the process between what's digital and what's physical and how we move between those two spaces is the one where I think creating that kind of ideal space to instantly affect the physical world" (personal communication, December 4, 2018)*

B points out that the tools that facilitate this process are still at the early stages of development, however, the concept is an important paradigm shift:

> *"A lot of those tools [Arduino] are really basic right now but this idea that we can sense the environment, take that data and process it and then affect the environment and then we sense it and do it all over again. It's a big paradigm shift that it's happening in real-time." (personal communication, December 4, 2018)*

4.24.4. Economics

Beyond general characteristics or specific features, economic considerations also play a role in architects' decision to choose a tool. E mentions that:

> *"It depends on who initiates the design. If it comes to me, I'm gonna use the Autodesk tools. They have a program called FormIt, which is kind of their response to SketchUp so it's a lighter weight 3D modeling program that you can also use with insight for energy and daylight analysis but it depending on some of the other people who like SketchUp start the model with SketchUp then we're gonna use Sefaira with the model they generated so it just depends on who's using it or who's starting it." (personal communication, December 4, 2018)*

In other words, since these software (FormIt and Sefaira) are designed in a way to work more consistently with other tools that are developed by the same company, choosing one has an important influence on choosing other tools. E argues that since in many cases, tools from competing companies do not work with each other seamlessly, the design team is forced to take this into account later stages before choosing the proper tool for a certain stage of the design process:

> *"The reason that you for example prefer that program to SketchUp is because you know at some point you want to convert it to Revit. […] There is a pipeline there in the workflow that's smoother or more seamless than adding a SketchUp model and then to take the SketchUp model and remodel everything basically in Revit. They don't talk well to each other." (personal communication, December 4, 2018)*

V provides an example of the kind of problems that arise when the design team needs to move between tools:

“one of our daylight modeling experiences, they did not have the simple element of, for example when you make like a frame of the window and you make the window panels and everything, they all were lost, so when you're converting it to Rhino you need them to be poly-surfaces, so they were made in such a way that they did not have a history of that, so the way the Revit model was constructed was not suitable for it to be converted into a Rhino model.” (personal communication, November 10, 2018)

4.25. Feature - All Stages Themes

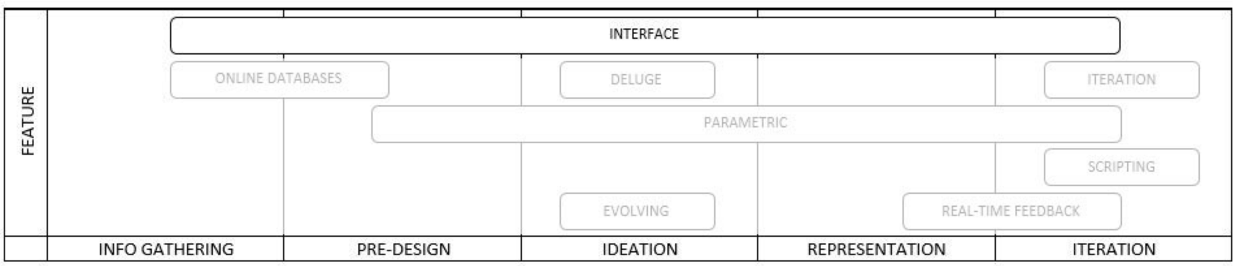


Figure 4-24 Feature - All Stages Themes

4.25.1. Interface

B points out that the idea of an interface is not unique to digital tools and even the manual tools have an interface: “there's an interface between the pen, the paper, [and] the desktop.” (personal communication, December 4, 2018) He argues that similar to manual tools, architects require a certain consistency in the interface of the digital design environment they use: “the consistency to set up the way we work, still means something, and so that difference is there, but, like, the way we think about it should, in my mind, be the same.” (personal communication, December 4, 2018)

Talking about 3Ds Max, AutoCAD, and Rhino, B points out that the consistency in the interface of AutoCAD and Rhino makes them better options to pair up while the different interface of 3Ds Max makes it more difficult to use as part of the design environment:

> *"it's actually it's removed from all of the ways the other software works and so something like AutoCAD and the way you use AutoCAD is much more similar to rhino and for me, like those two it's just a no-brainer why you would pair all of that together, so I wouldn't force 3ds MAX on my students" (personal communication, December 4, 2018)*

V argues that without a simple interface to perform glare analysis, architects would not invest time and money on incorporating that into the design process:

> *"unless you have like a software which is like so efficient that you don't have to spend time and the transition is as much as like double like one or two clicks and you get this glare analysis if it's as simple as that people will do it but if you have to make a model and spend time doing like you should have it like simultaneously like if you're doing if you're getting the first two points and you want to get the third one you should use the same bottom to do all three analysis you gonna get you gonna do that otherwise people don't have time and people the architects don't pay you sufficient money to do this analysis" (personal communication, November 10, 2018)*

E, with regards to Sefaira, talks about how its' interface is good for the early stages of design when there are not many details in the model. However, the interface becomes limiting at later stages when there are many details and surfaces to include:

> *"Sefaira definitely is good for early on getting the window size and in the right places for balancing special daylight autonomy versus glare things like that but once you know once that model becomes really heavy… it's weird because you have to assign parameters to surfaces so it becomes really cumbersome in terms of… once the model gets developed to maintain those parameters to ensure that the analysis is correct. In that, at some point, it becomes the model becomes too big for that plugin." (personal communication, December 4, 2018)*

This suggests that related to the *evolving* theme, the interface also needs to evolve as the design proceeds. In contrast to Sefaira, V argues that Grasshopper provides a proper interface for these tasks, even at later stages of the design process: "if you use Grasshopper you know it's very simple to apply materials, it's very simple to run a daylight analysis and all." (personal communication, November 10, 2018)

4.26. Summary

The interviews enabled me to provide more details and expand the framework substantially as it is illustrated in Figure 4-25.

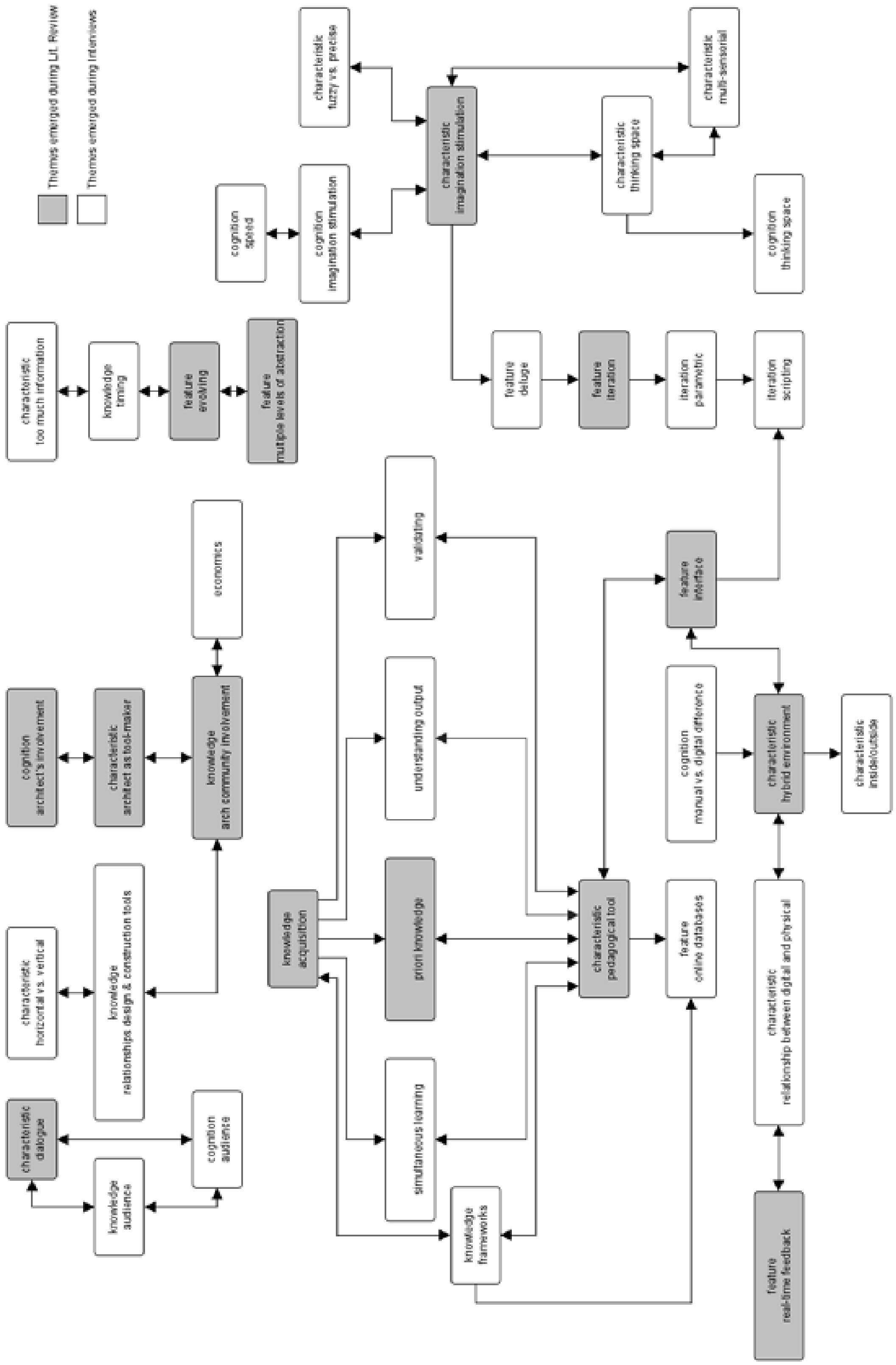


Figure 4-25 Themes emerged during the literature review versus those emerged during the interviews

The central themes (*Imagination stimulation*, *Knowledge Acquisition*, *Hybrid environment*, *Architect as toolmaker and design environment coordinator*, and *Interface*) all initially emerged during the literature review. However, two of them, *Interface* and *Hybrid environment*, which were outlined during the literature review were developed substantially as the result of the interviews.

Also, the interviews helped me to better understand these themes in relation to one another. As a result, the interviews enabled me to map out the first draft of the thematic relationships and interconnections as it is illustrated in Figure 4-25. The thematic relationships were further investigated and modified during the immersive case study and the Delphi method steps.

5. Immersive Case Study

5.1. Introduction

As described in chapter three (methodology), I used the immersive case study as a method to expand the themes that emerged during the literature review and interviews. The case study was designing a community center for a housing project in Charlottesville, Virginia. This project was chosen because the program provided a good opportunity to investigate how best to synthesize both qualitative and quantitative criteria. The project is located on a hilltop wooded site that provides unrestricted views in various directions. Also, since the project is intended to be an eco-friendly housing complex, the program requires showcasing sustainable design strategies.

During the design process, I kept a journal of all my design proposals and studies. I documented my reflections on the process in light of the themes that were developed in the previous phases of the research. I tried to keep my notes as detailed as possible in order to document my thinking process. Also, I tried to prolong the early stages of the design process by withholding decisions concerning the details of the design, since this research is mainly concerned with the early stages of the design process.

As mentioned in the introduction to chapter four, chapters four and five serve as the main results chapters. Therefore, the sections in these chapters are presented in an order intended for clear referencing. For a more comparative discussion of the themes, please refer to chapter 7 Conclusion.

5.2. The Tools

There are many tools and services used and discussed in this chapter. This section is intended to be a reference for all these tools and services. It begins with a short description of each tool in alphabetic order and is meant to eliminate the possibility of confusion by the reader.

2030 Palette (2030Palette.org): an online educational project in collaboration with organizations such as the American Institute of Architects (AIA), U.S. Green Building Council (USGBC), Autodesk, etc.

ArchDaily (archdaily.com): an architecture community news portal that includes a public database of architectural projects' profiles with images and drawings.

AutoCAD: a commercial computer-aided design (CAD) and drafting software developed by Autodesk since 1982.

Climate Consultant: a free software developed by the University of California, Los Angeles (UCLA) Department of Architecture and Urban Design for graphical representation of climate data.

CoveTool (covetool.com): an online and cloud-based energy analysis platform. It uses energy calculations defined by ISO 13790 and CEN 15603 (Ahuja, n.d.) and is one of the tools suggested by the 2030 Palette.

Diva: a daylighting and energy modeling plug-in for Rhino and Grasshopper, initially developed at the Graduate School of Design at Harvard University.

eQuest: an energy analysis software based on DOE-2, funded mostly through the United States Department of Energy (USDOE).

Google Cardboard: a cardboard mobile virtual reality headset.

Grasshopper: a graphical scripting environment, developed as a plugin for Rhino.

Medeek Truss: a plugin for SketchUp for modeling truss systems through a parametric graphical user interface.

Microsoft Surface Studio: an all-in-one PC with a hinge design screen enabling it to be tilted to various angles.

Modelo (modelo.io): an online service for viewing 3D models in several formats including Rhino, Revit, and SketchUp in mobile VR headsets such as Google Cardboard.

Oob Terrain: a plugin for SketchUp for importing the site’s terrain, texture, and surrounding buildings from online services such as Google Earth and Open Street Map.

Photoshop: a raster graphics editor developed by Adobe.

Revit: a commercial building information modeling (BIM) software developed by Autodesk.

Rhino: a commercial 3D modeling and computer-aided design (CAD) software developed by Robert McNeel & Associates.

SkechBook Pro: a raster drawing and sketching software developed by Autodesk.

SketchUp: a 3D modeling software developed by Trimble.

Unity: a game engine developed by Unity Technologies.

Wacom: a series of drawing tablets developed by the company Wacom.

5.3. The development of the Themes

As discussed in chapter four, an important outcome of this research, beyond the development of the themes separately, is to gain a deeper understanding of their thematic relationships and interconnections. Moreover, this research tries to document the evolution of these themes and their interconnections through each stage of the research. Therefore, by comparing Figure 5-1 and Figure 5-2 in this chapter to the corresponding figures in chapter four, the reader can have a clear picture of this evolution. (refer to conclusions in chapter 7 for more discussion about the evolution of the themes)

Logically, not all themes were explored in all stages of the research. Some of the themes discussed in chapter four are not further explored in this chapter, while some new themes did emerge at this stage of the research that, naturally, are not discussed in the interviews. Some themes are expanded substantially, while others developed in minor details. The triangulation of the methodology was in anticipation of this. Studying these trends, as presented in the conclusions in chapter 7, clearly illustrates the relative importance of these themes.

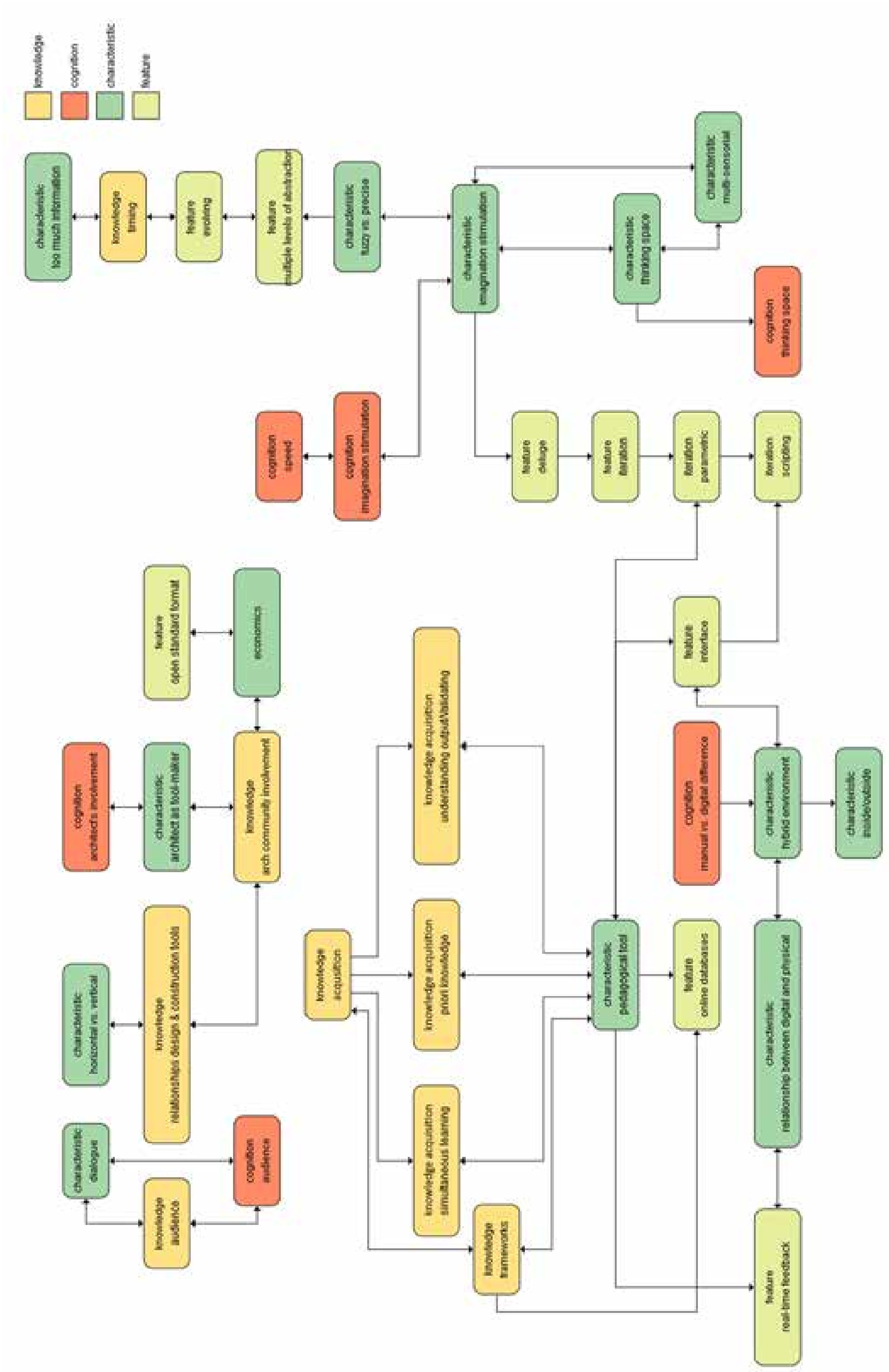


Figure 5-1 Themes Interconnections at the end of the Immersive Case Study

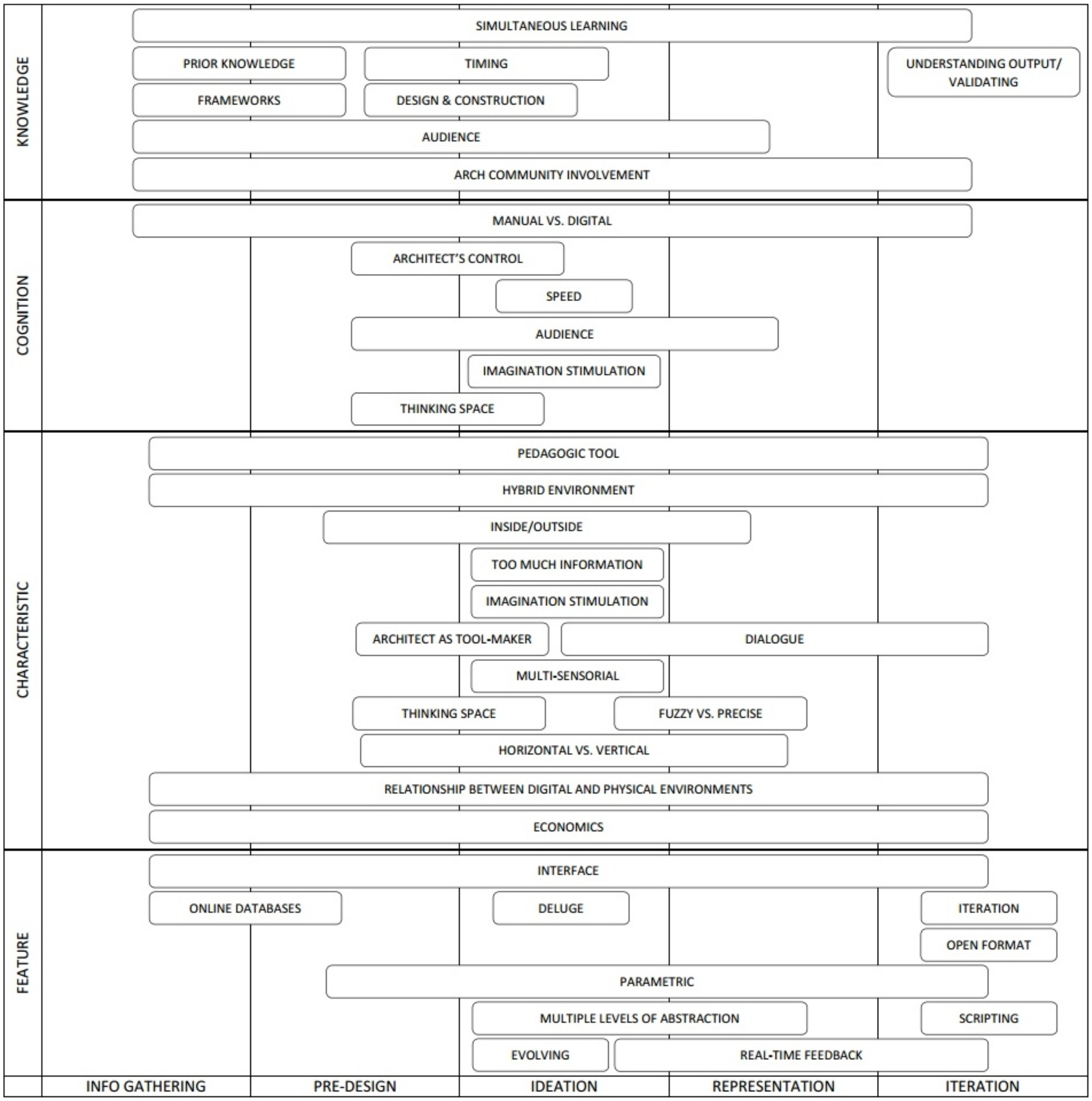


Figure 5-2 Themes in relation to design process stages at the end of the immersive case study

5.4. Characteristics - Ideation Themes

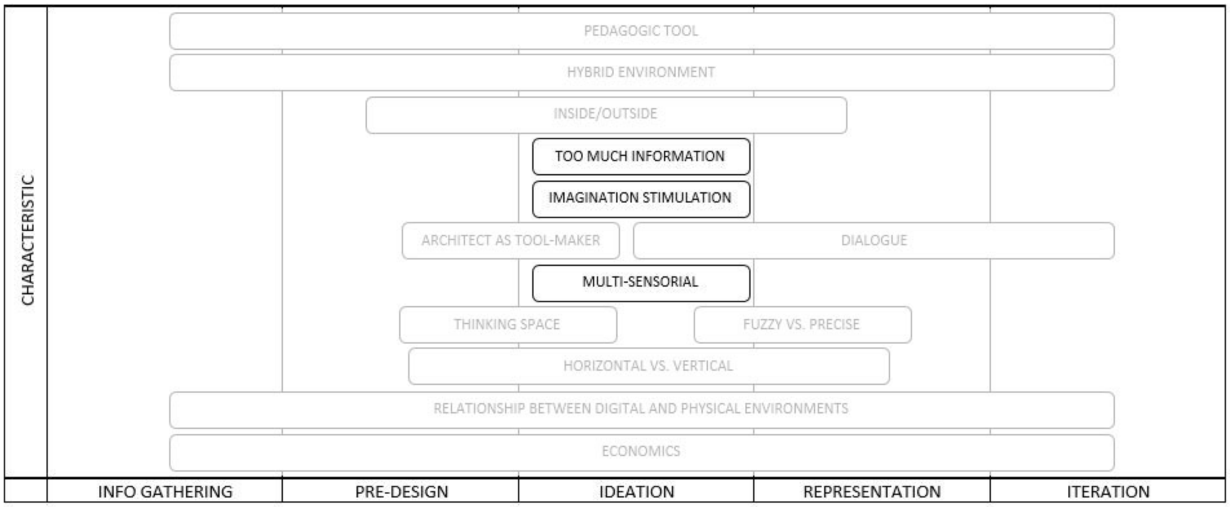


Figure 5-3 Characteristics - Ideation Themes

5.4.1. Multi-sensorial

I have argued in my journal that while working on the physical model since I am closely working with materials (have a haptic interaction with the design), I have a better sense of the materiality of the design. For instance, at a certain point, I reach this intuitive decision that the material for the roof of the administrative area needs to be different from the surrounding surfaces to prevent the design from getting too monotonous. (Figure 5-4)

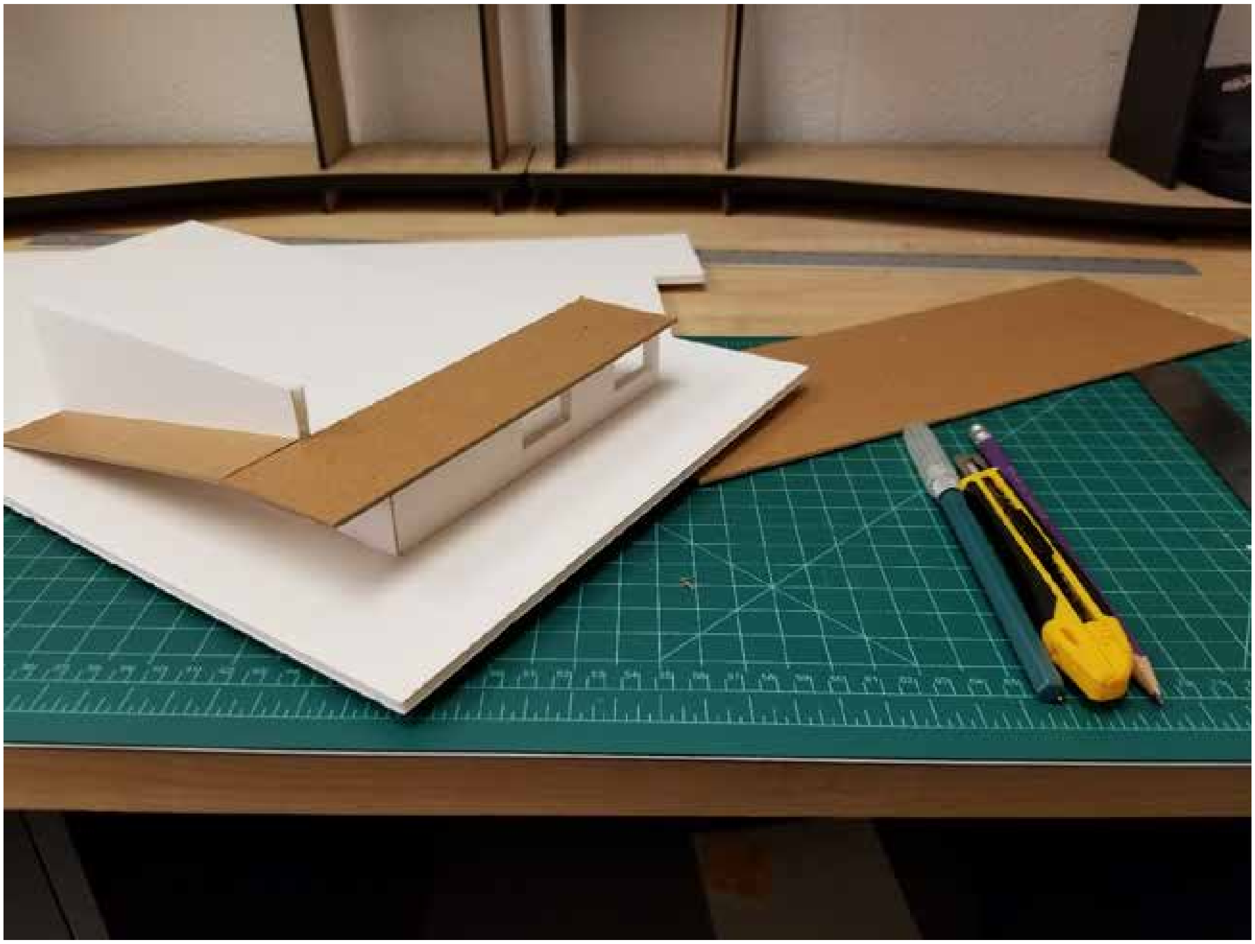


Figure 5-4 Adding the administrative area's roof to the model

I have documented listening to Goldberg Variations by Bach while working on the physical model. Aaron Copland argues that:

> *“music provides the broadest vista for the imagination since it is the freest, the most abstract, the least fettered of all the arts: no story content, no pictorial representation, no regularity of meter, no strict limitation of frame need hamper the intuitive functioning of the imaginative mind.” (1980, p. 7)*

The use of music as a stimulus of imagination has been documented by artists in other fields too. For instance, there is a scene in the documentary *10 Years with Hayao Miyazaki* (Arakawa, 2019) during which Miyazaki (the famous Japanese animator), who has been struggling to come up with a new idea for his next film, listens to the opening piece from the third act of The

Valkyrie by Wagner. While listening to the music, he draws a sketch that ends up being the starting point of his next project.

Referring to visual sources to stimulate the imagination is a common practice among architects. I have mentioned in my journal going through and saving architectural images at the beginning of the design process. However, the examples in this section show the importance of the stimulation of other senses during the imaginative processes.

5.5. Feature - Ideation Themes

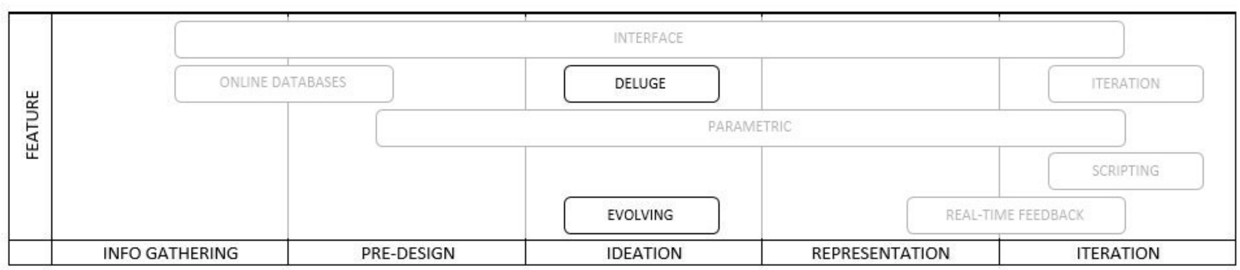


Figure 5-5 Feature - Ideation Themes

5.5.1. Evolving

In the interviews in chapter 4, V provided the example of using eQuest as a design tool where the simulation model evolves as the design develops. In other words, the use of the tool corresponds to the demands and characteristics of the different stages of design.

Figure 5-6 represents the main input window in eQuest for the three stages of the project. The top image is from the Schematic Design Wizard, used at the early stages of the design process. The middle image is from the Design Development Wizard, used later on when more details are available. The bottom screenshot is from the Detailed Interface which is used for advanced modifications at the final stages of the project. As shown in these screenshots, the interface gets more complex and input detailed as the design develops.

This feature enables the user to develop complex and reliable energy models early on without being restricted due to a lack of detailed information. In other words, the tool requires only abstract information that is known to the user at that stage and fills in the missing information with standard default inputs. However, as the design developed and more information becomes available, the tool allows the user to modify those standard default inputs and make the model more representative of the actual design.

This scenario is closely related to the *timing* theme where the evolving design features are accommodated in eQuest through the multiple user interfaces.

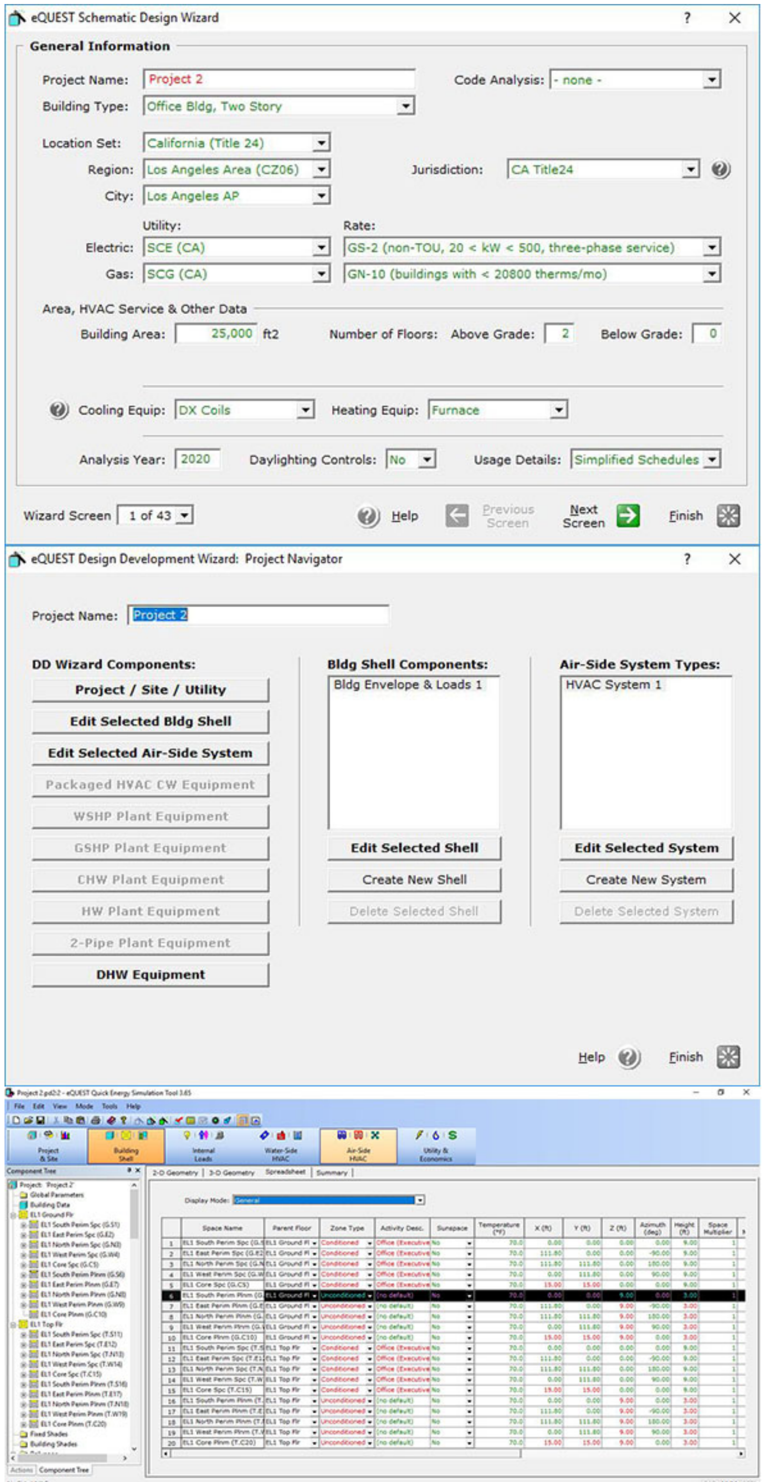


Figure 5-6 eQuest SD Wizard, DD Wizard, and Detailed Interface

Another example of a working environment that does not support the evolutionary nature of design is Revit. (Figure 5-7) When deciding on what software to use for the initial 3D model, I noted that Revit should be avoided in the early stages due to the large amount of information needed to generate the model. A conceptual massing study feature is not available in Revit and the modeling environment is still far too rigid for the early stages of the design process. For this reason, I preferred to use SketchUp early on while accepting the need to transfer the model to Revit at a later stage. However, the key point here is that a working environment or combination of tools must be able to support the evolution of the design. To avoid the time and effort of transferring the model between tools, best would be to either add a conceptual massing environment to Revit to support early-stage exploration or provide a translator to efficiently move from SketchUp to Revit. With either of these approaches, the early-stage massing model later becomes the foundation for developing the detailed Revit BIM model, thus making the overall process more efficient.

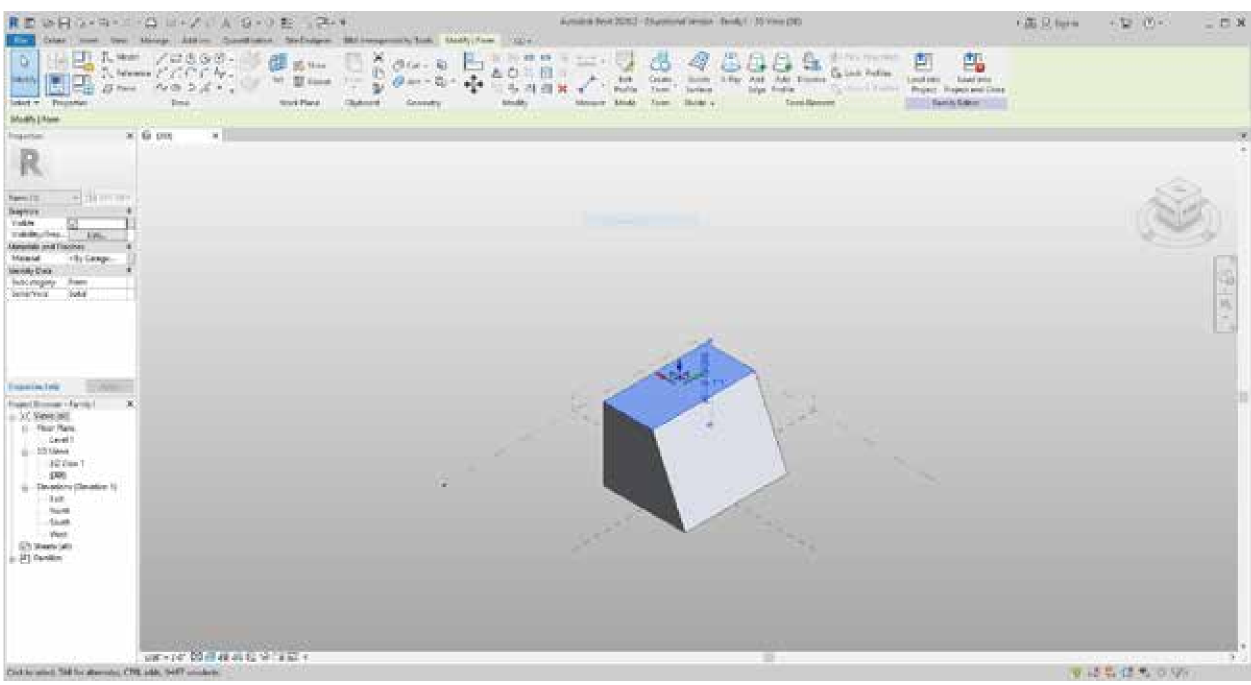


Figure 5-7 Revit Conceptual Massing Environment

5.5.2. Deluge

In previous Chapters, I have discussed the concept of deluge; the discovery of unintentional outcomes that can help to stimulate the imagination. I have documented one instance of this in my journal. While working on a physical model, after drawing guidelines on the board with my pencil I cut a piece of foam-core to represent a wall. Afterward, looking at the backside of the piece, I realized that without the guidelines the wall looks dull, while with the guidelines, a clear and understandable sense of order is achieved. (Figure 5-8)

Figure 5-8 The wall piece, showcasing the pencil guidelines

The *Deluge* theme relates to what has been discussed in the literature review chapter regarding the design problems being ill-defined and ill-structured. It is due to this characteristic of the design problems that many times the architect is not able to define the goals of a design task until the task is done or as Cross puts it: “[designers need to] define, redefine and change the problem-as-given in the light of the solution that emerges from their minds and hands.” (2006, p.

7) Therefore, any design environment that requires a clear definition of the goals before embarking on a task, such as Revit, limits the architect in addressing this characteristic of the design problem.

5.6. Knowledge - Iteration Themes

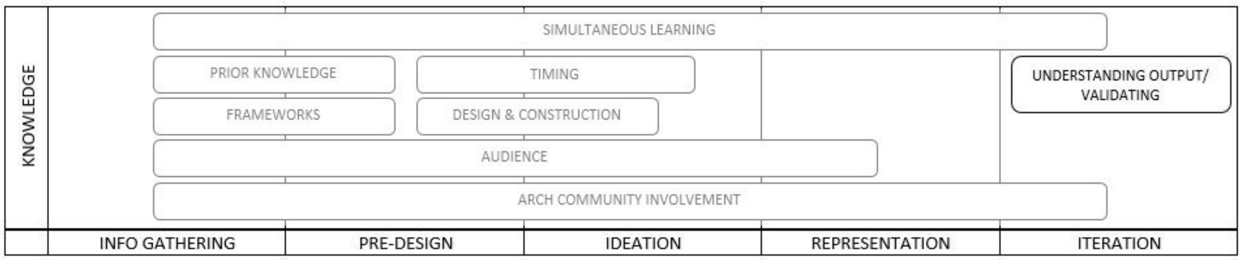


Figure 5-9 Knowledge - Iteration Themes

5.6.1. Understanding and Validating Output

Both CoveTool and eQuest were used as energy modeling tools. I noted in my journal that the simplistic approach to inputting descriptive information in CoveTool (as compared to eQuest for example) makes me suspicious about the reliability of the results. For instance, for defining the construction of the building envelope, CoveTool only provides a series of boxes (cramped between many other boxes) to insert U-values. (Figure 5-10) I noted that “it makes me lose confidence in the results”, particularly when I realize that U-value inputs alone do not account for thermal mass and time-lag effects that could be influential. (2020) This suggests, that finding the correct balance between the ease of use and input and the reliability of the process, particularly for quantitative assessment, is an important consideration when selecting or developing a design support tool.

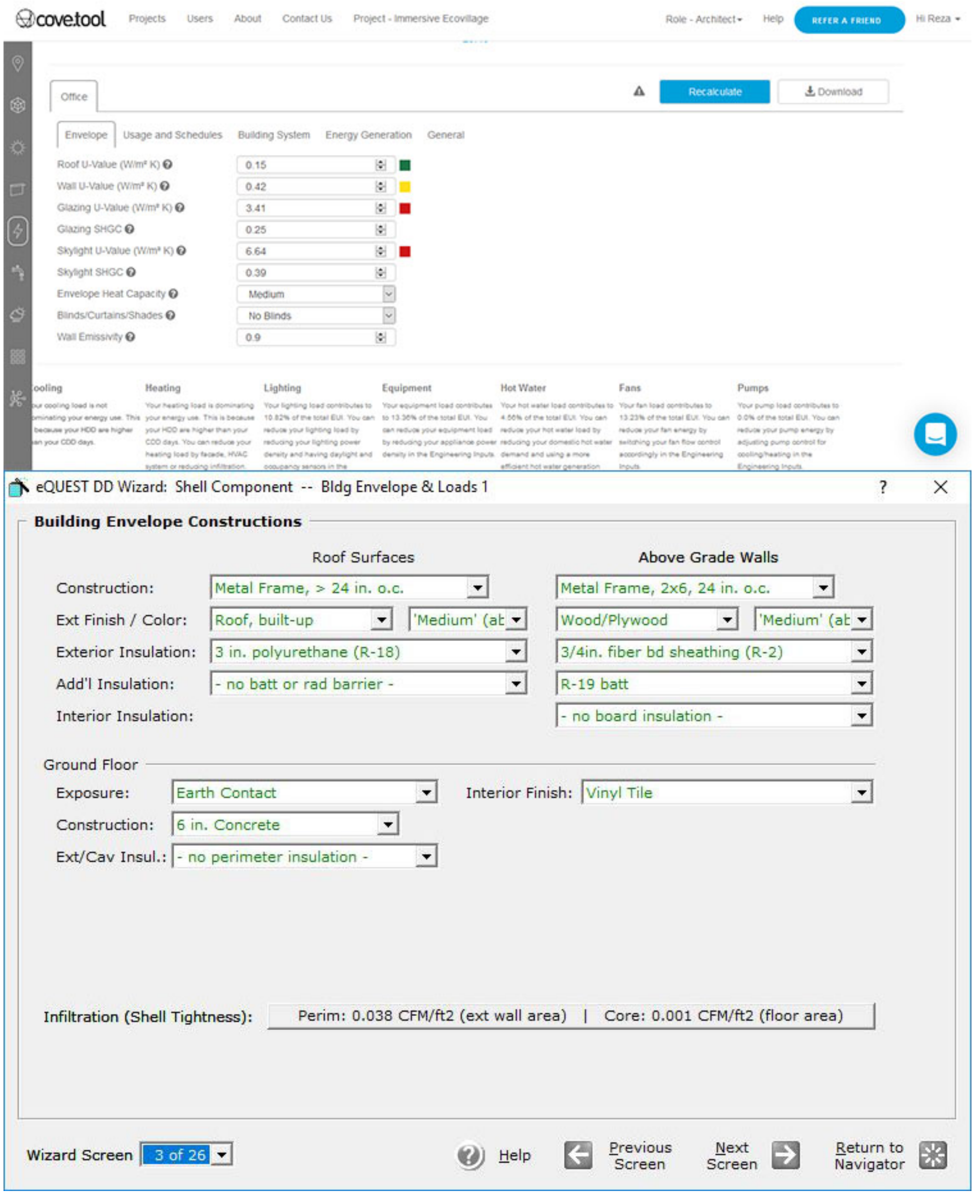


Figure 5-10 Building envelope's construction input screen in CoveTool (top) versus eQuest (bottom)

5.7. Features - Iteration Themes

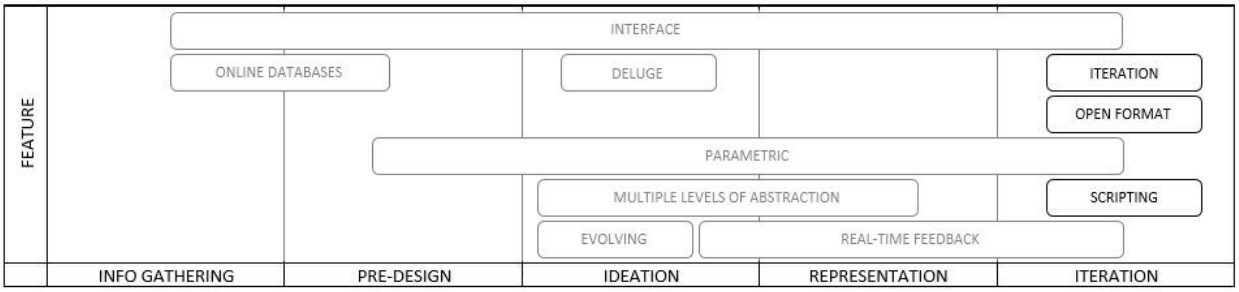


Figure 5-11 Features - Iteration Themes

5.7.1. Scripting

I have documented in my journal an incidence of trying to reuse a Grasshopper script from a previous project. This script was initially developed to study shadow patterns using Diva's sun path component. For the immersive case study, I wanted to use this script to study the effect of the angle of roof pitch on the amount of shadow that would fall on an array of PV panels located on the roof. I have noted that the process of using the script was very easy and all I needed to do was to change the input of the geometry component to the new 3D model. This is a good example of the power of scripting and the use of visual scripting interfaces to automate common design studies that are usually performed by the architect.

Also, the scripting interface provides the user with a high level of control. For instance, to access raw data (such as the numeric values produced at different points of the algorithm) and use them for various design studies. As an example, I have documented a process of exporting the sun altitude angles at the summer and winter solstice from the Grasshopper script mentioned above. Using these angles, I studied the depth of the shading required for a greenhouse space in order to let the sun in during the winter months and provide shade during the summer. (Figure 5-12)

The scripting interface, especially visual scripting environments such as Grasshopper, provides a clear picture of the flow of the information. As discussed above, this feature helps with:

1. Reusing scripts to perform and automate repetitive steps of design studies since it is easier for the user to understand which steps (components) need to change and which steps remain untouched. This highlights the importance of the development of local and online script libraries.
2. Modify certain steps of a study to perform a new study since it is easier to comprehend the uniqueness of each step and therefore add or remove steps as needed.

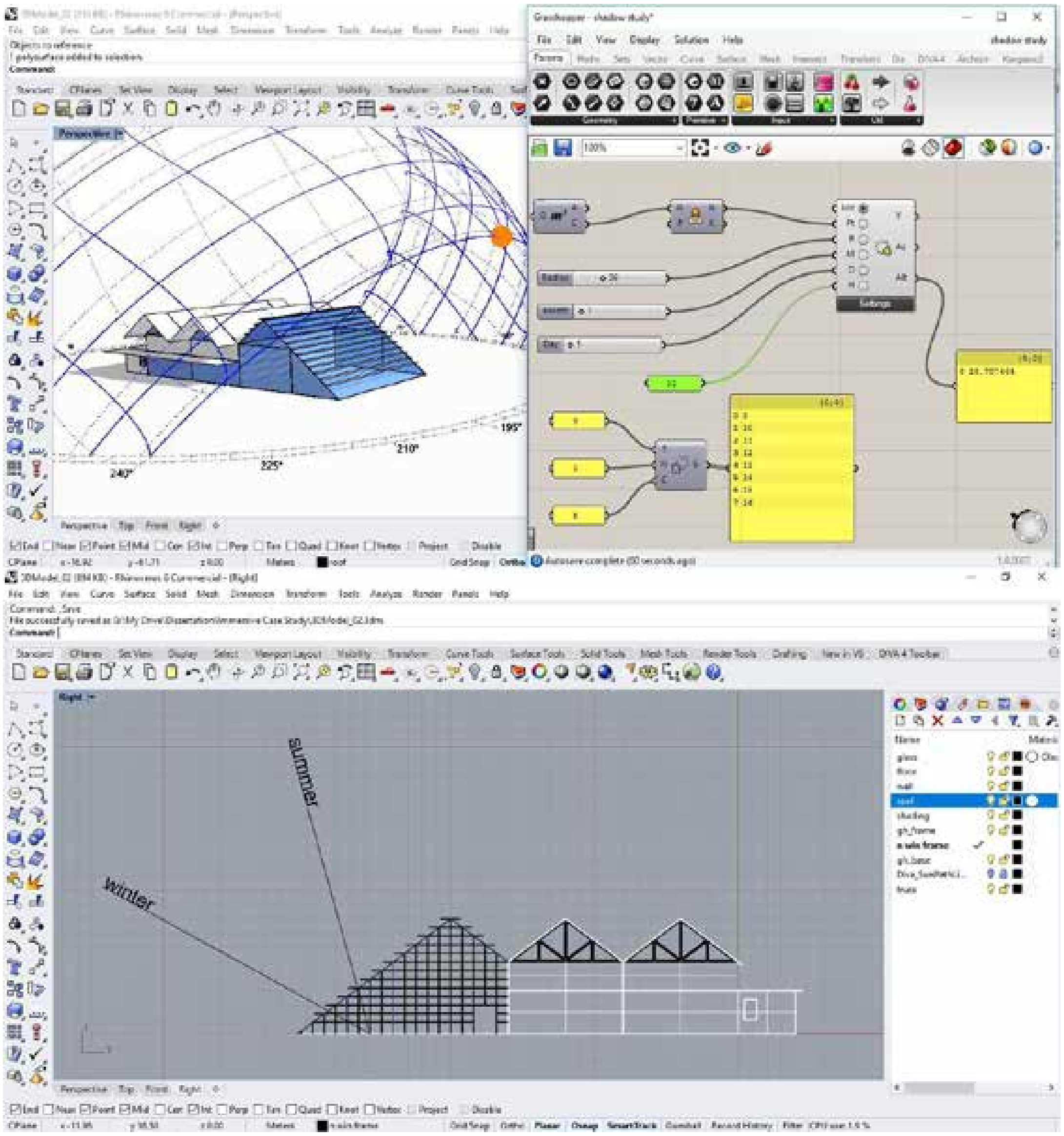


Figure 5-12 Sun path study using Diva in Grasshopper (top) sun angle relative to greenhouse shading (bottom)

5.7.2. Open Standard Formats

In an effort to facilitate interoperability between various digital platforms, including 3D modeling programs, and supporting the iterative process during design development, the architecture community (academics in specific) should advocate for open and standard file formats. A good example of such efforts is the development of the Open Document Format for

Office Applications (ODF) by the Organization for the Advancement of Structured Information Standards (OASIS) consortium. Through the effort of OASIS, the ODF format has been recognized by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC).

For architectural applications particularly quantitative performance estimation, until such formats are widely adopted, the CoveTool approach is a useful workaround. This is because CoveTool offers a plugin for each of the major 3D modeling platforms, including SketchUp, which prepares the model for uploading to the CoveTool website.

5.8. Knowledge - Info Gathering/Pre-Design Themes

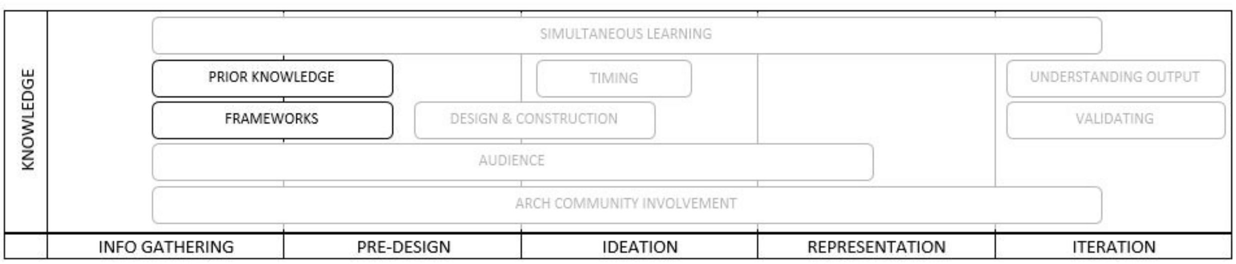


Figure 5-13 Knowledge - Info Gathering/Pre-Design Themes

5.8.1. *A Priori* Knowledge

I have documented instances of lacking required *a priori* knowledge and finding it necessary to go through a learning episode before being able to perform a task. For example, I have noted that for performing the glare analysis, I needed to learn what 30% DGP means. For this, pedagogic tools (refer to Pedagogic Tool) can greatly simplify and expedite the learning episode by guiding the user toward the right resources.

The problem of lacking required *a priori* knowledge is more evident for energy modeling since it requires a substantially larger number of inputs from the user. Although concepts such as U-value is expected to be covered in architecture schools' curricula, others such as details of different HVAC systems are less likely to be covered in building systems courses. In such cases, short explanations for each input field (as described in the case of eQuest and CoveTool in the Pedagogic Tool section) can help to resolve this problem.

5.8.2. Frameworks

I have discussed the concept of frameworks as a bundled set of information that helps the architect to frame the design question. A good example of such frameworks is the 2030 Palette Portal. This Palette portal provides strategies for sustainable design (Figure 5-14) with each entry covering the following information:

A short explanation of the strategy

Pictures of projects which employ that strategy

Related strategies (you might want to consider)

Books that cover that strategy

Tools that help to incorporate that strategy into the design

Since the program for the case study required showcasing sustainable design strategies, I referred to the 2030 Palette portal during the pre-design stage to find more information about possible strategies that can be included in the design. Also, I used the portal later during the design process when I was developing the idea of a greenhouse as part of the design and I wanted to make sure that I am incorporating this strategy correctly.

The recommendation of tools is a unique feature in the 2030 Palette portal. For instance, the portal recommended CoveTool as one of the possible tools for studying the effect of the strategies I was interested to incorporate into the design. Such recommendations are an important requirement for actualizing the concept of the architect as a toolmaker introduced by Davis and Peters (2013) (discussed in the literature review section). Here they do not mean that the architect is the developer of the tools but rather they see the architect as the person who connects various tools together and thus creates a unique constellation that helps to define the design problem from a certain perspective. This is seen as one of the contributions for the present work.

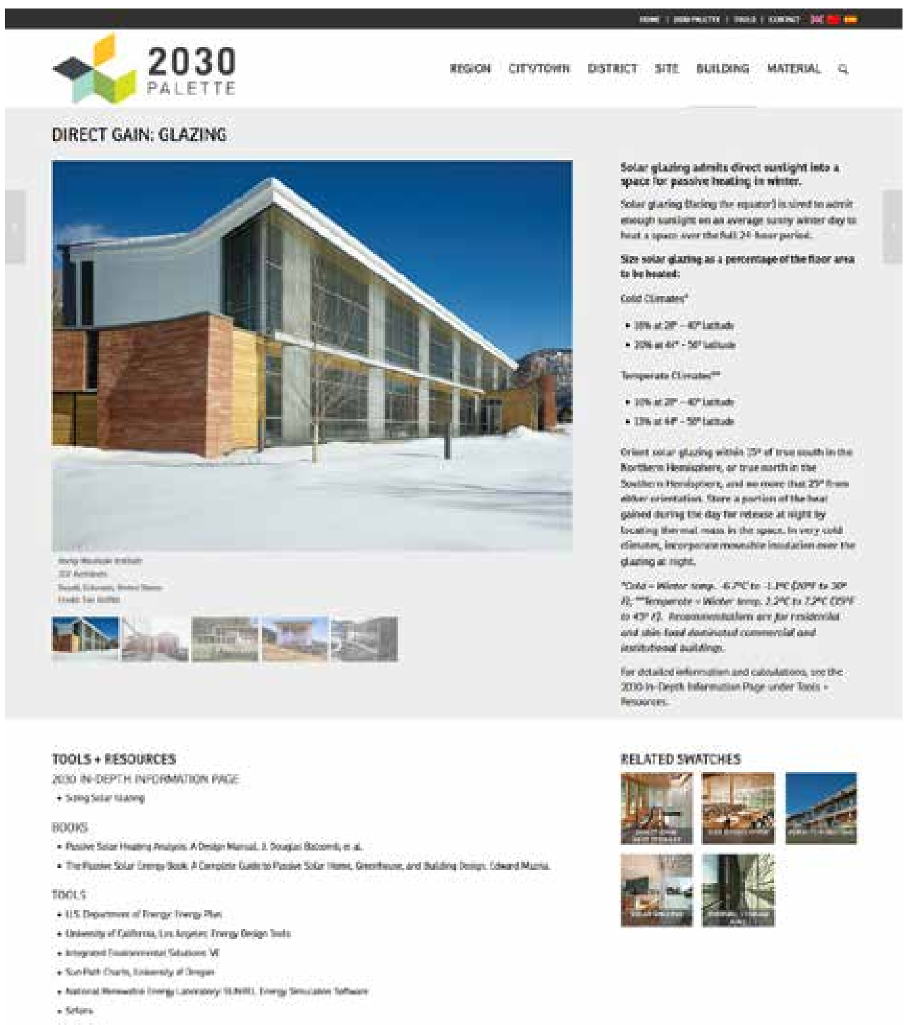


Figure 5-14 A Sample entry from 2030Palette.org

Another example of a Framework used in the Immersive Case study was videos accessible through services such as YouTube. Selected videos were used to improve my knowledge of certain tools or skills needed throughout the design process. For example, when conducting the glare analysis using Diva, I watched a video produced by the MIT Sustainable Design Lab, which helped me better understand how to use the tool. In another instance, for performing a shadow study using Diva, I watched a video produced by Solemma, the company behind the development of Diva. This helped me understand the inputs and outputs of Diva's sun path component. There were several reasons for choosing these pedagogic materials (videos) over other available resources:

1. They are produced by people who I trust, i.e. the developers themselves or reputable academic institutes.
2. I had a clear understanding of approximately how much time would be required to learn the skill (the length of the video).
3. I could easily go back and forth, skip through parts that I do not need, and repeat more important parts.

An important consideration when implementing these knowledge frameworks is the user-friendliness of the interface. In other words, how well was the information presented to the architectural community? For instance, the Climate Consultant software is basically a front-end design support tool for processing weather data files. The output includes Psychrometric charts and design guides that can help with decision-making. (Figure 5-15) Tools such as this which provide access to a knowledge framework become, in my terminology, "pedagogic tools". Similar to the use of Climate Consultant, after getting acquainted with 2030 Palette, I have documented a number of instances of referring to the 2030 Palette website early in the process for more information concerning design strategies such as using a greenhouse as a passive heating strategy.

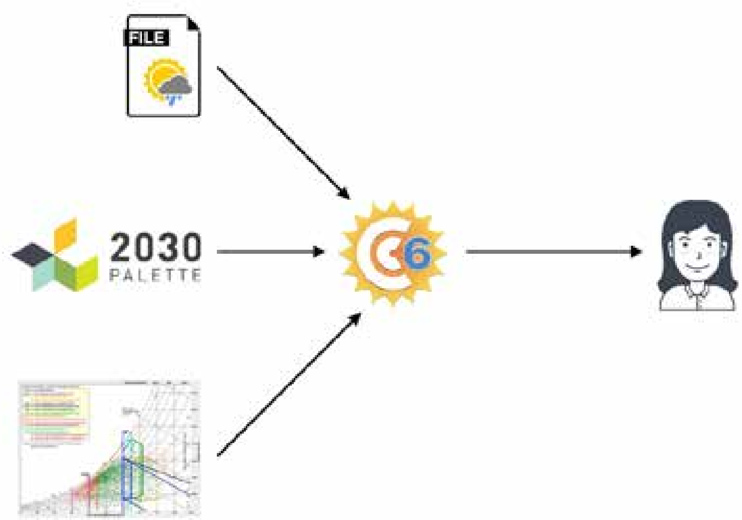


Figure 5-15 Climate Consultant as a knowledge framework interface

Such interfaces can help use other knowledge frameworks such as building codes. I have documented an instance in my journal of a problem finding the correct building code related to determining the number of bathroom fixtures required for the community center. Considering that building codes are well-organized documents, accessing them during the early stages of the design process could be a much more straightforward process when using a well-designed online interface.

5.9. Feature - Info Gathering/Pre-Design Themes

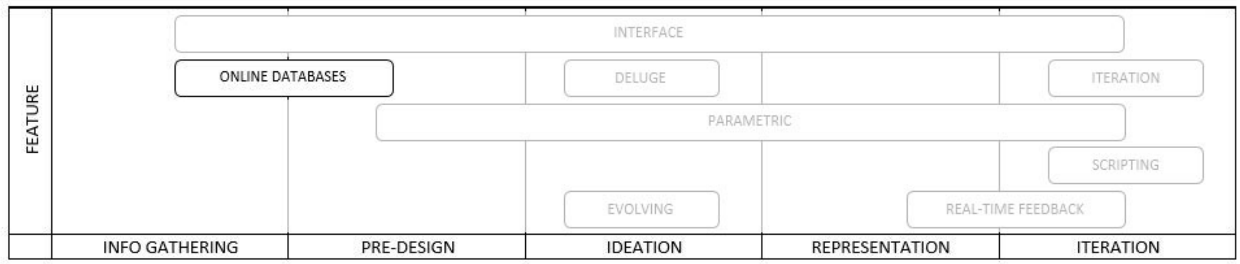


Figure 5-16 Feature - Info Gathering/Pre-Design Themes

5.9.1. Online Databases

As part of a pre-design and information gathering stage, I used Google Images as an online database of images, and precedent studies for “community center”. For this, I created a digital folder that contained images that were found to be of interest. Some images showed specific design solutions that had interesting features. For example, I noted that a pergola at the entrance was often used.

Google Images offers filters for certain drawing types such as floor plans or certain aesthetic qualities such as “Modern”. (Figure 5-17) The floor plan filter led me to study various approaches to community center plan layouts. I have documented three options in my journal. (Figure 5-18)

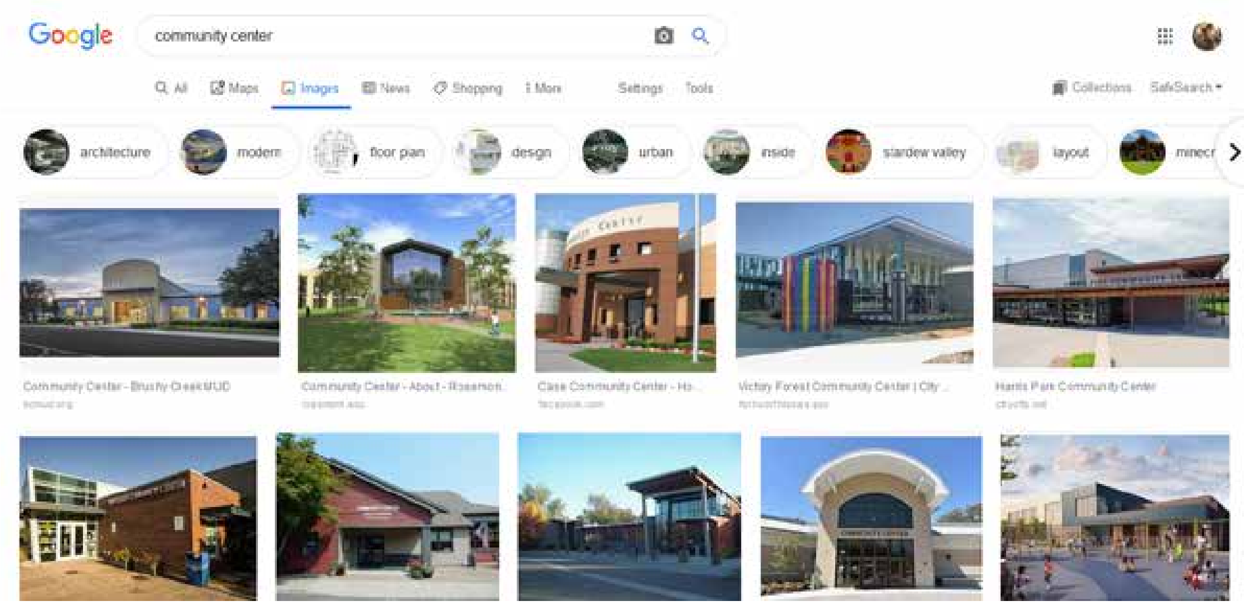


Figure 5-17 Search results for a community center in Google Images

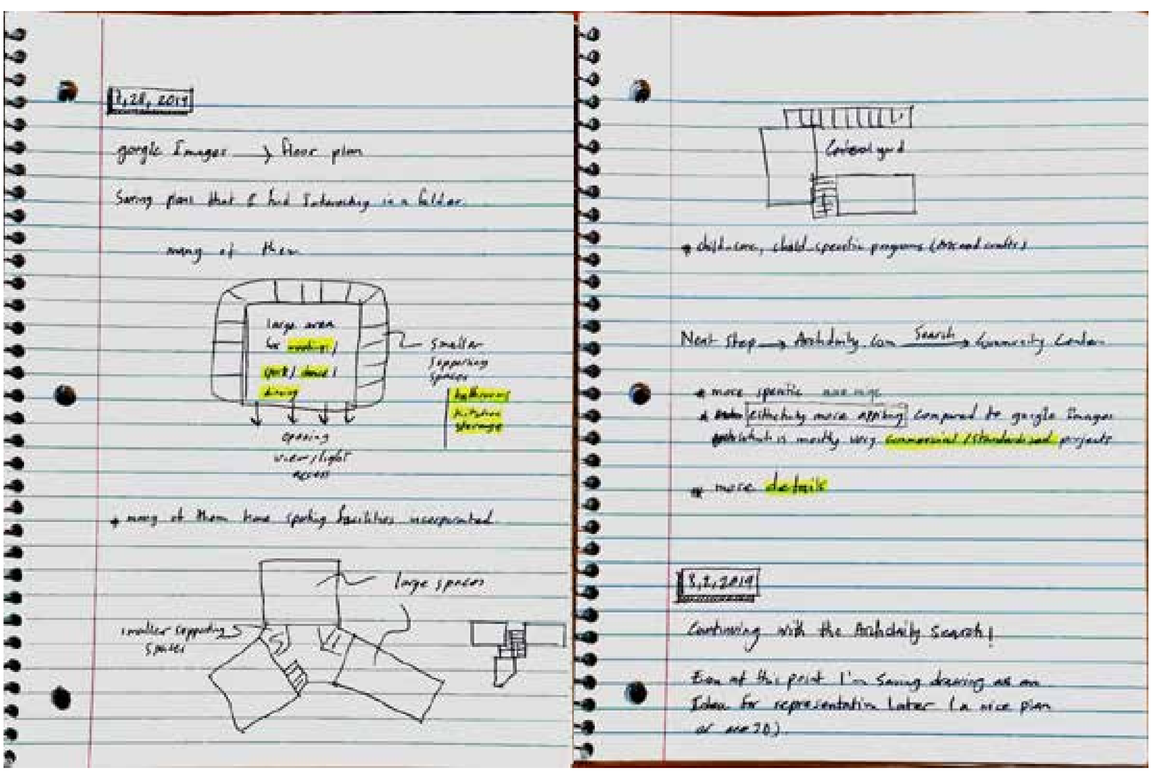


Figure 5-18 Three Categories for Community Center Plan Layout (Personal Journal)

As the next step, I switched from Google Images to ArchDaily, to continue the information gathering and pre-design studies. ArchDaily is a platform more specifically targeted toward architects. I have compared the results from these two online databases in my journal and have noted that:

Results from ArchDaily were more specific. In other words, there were more projects similar to mine, while considering the scale and program requirements.

Results from ArchDaily were more unique while results from Google Images were mostly commercial/standardized constructions.

Results from ArchDaily included more details.

I have noted in my journal that ArchDaily has the option to filter the results based on categories such as the country/region, year, or even color Palette. (Figure 5-19)

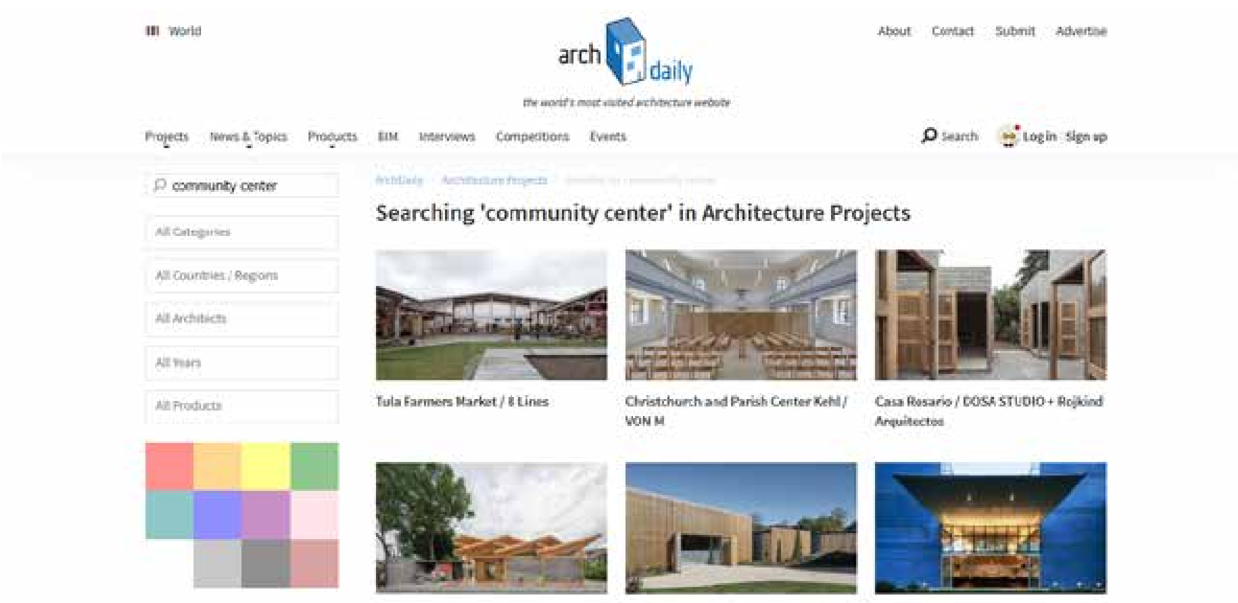


Figure 5-19 Search results for a community center in ArchDaily

Additionally, I have documented many instances of referring to online databases at various stages of the design process: www.archweb.it for 2D blocks and details while working in AutoCAD, www.dimensions.guide for accessible bathroom dimensions.

5.10. Knowledge - Pre-Design/Ideation Themes

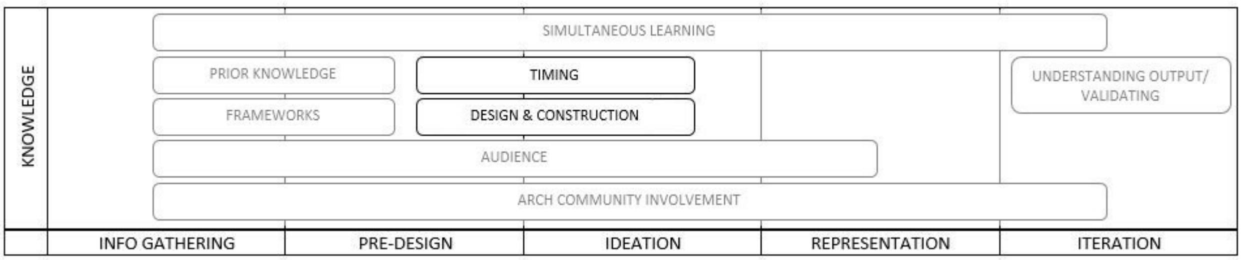


Figure 5-20 Knowledge - Pre-Design/Ideation Themes

5.10.1. Timing

In the interviews in chapter 4, I argued that when developing a tool for architectural decision-making, the developer should consider questions such as:

> When (during the design process) would the architect need useful decision-support information that the tool can provide?
>
> What information should the architect know to be able to make related decisions?
>
> Does the architect have access to information at the proper stage of the design process?

As previously mentioned, eQuest is a good example of an energy modeling tool that addresses these questions. For instance, the eQuest user guidelines suggest using the Schematic Design Wizard (which asks for fewer inputs) during the early stages of design and then moving to the Design Development Wizard in later stages, when more detailed information about the design is available. (Figure 5-21)

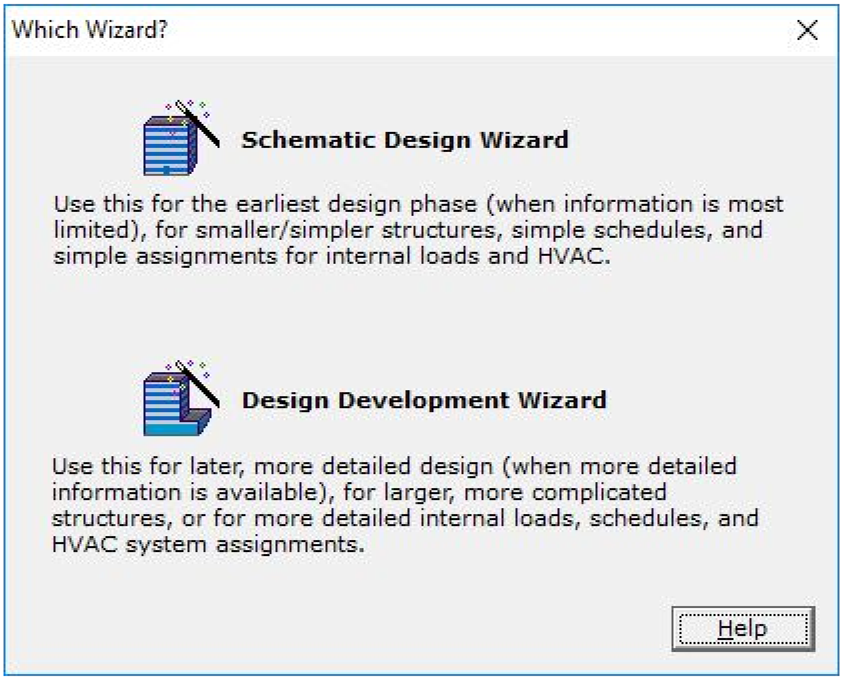


Figure 5-21 eQuest Wizards

Another good example of appropriate Timing concerns Climate Consultant. The developers of this tool point out that the purpose of the program is to "help architects, builders, contractor, homeowners, and students understand their local climate […] the purpose is not simply to plot climate data, but rather to organize and represent this information in easy-to-understand ways that show the subtle attributes of climate, and its impact on built form." (*Energy Design Tools*, n.d.) In other words, the purpose of Climate Consultant is to enable architects to have access to weather data in an easy-to-understand format in the very early stages of the design process.

Another example of the timing associated with the use of Climate Consultant is the sequential progression from the design guidelines screen to the wind wheel. In this order, the architect first considers general guidelines for issues such as the orientation to the sun and the prevailing wind direction. The proper siting of the building relative to the prevailing wind direction requires interpretation of the wind-wheel diagram.

5.11. Cognition - Pre-Design/Ideation Themes

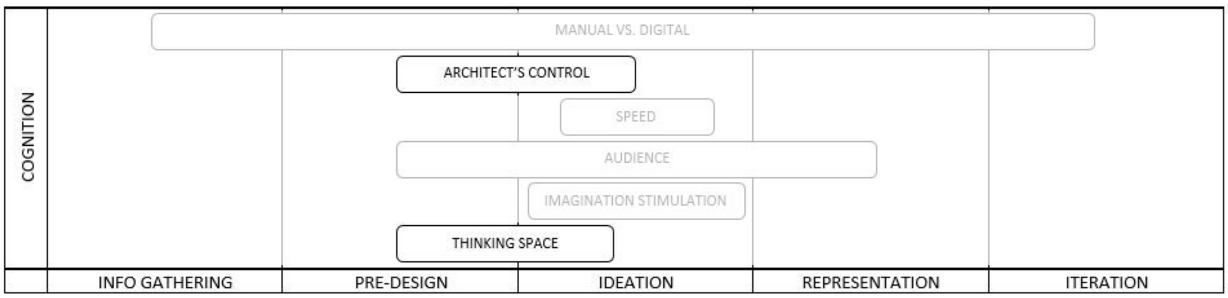


Figure 5-22 Cognition - Pre-Design/Ideation Themes

5.11.1. Thinking Space

I have noted in my journal that working on the physical model has a meditative effect. I have associated this feeling with the craft and hands-on nature of making a physical model that involves the influence of the materials used. I believe that this mind-body interaction creates a mental space that supports design thinking.

5.11.2. Architect's Control

As an example of lack of control when using a tool, while studying the report produced by CoveTool, I noted that even though the report is well designed and graphically appealing, it includes information (such as results of a glare analysis) that I did not provide input for. I would suggest that this lack of control over the input makes me question the validity of the results.

eQuest too provides default values for inputs to reduce the possibility of overwhelming the user at the early stages of the design process. However, in contrast to CoveTool, eQuest maintains the architect's control over the process by walking the user through these default values using the wizard interface. Therefore, even when the results are produced with the same amount of default values for inputs, I am more confident about the validity of the results of eQuest, compared to the results of CoveTool.

Moreover, eQuest uses different colors to distinguish default values from those provided by the user (green for default values and red for user inputs). (Figure 5-23) This feature enables the user to have a clear understanding of what inputs are left as default values and which ones are modified. Therefore, the user can easily reduce default values in each iteration as the design progresses.

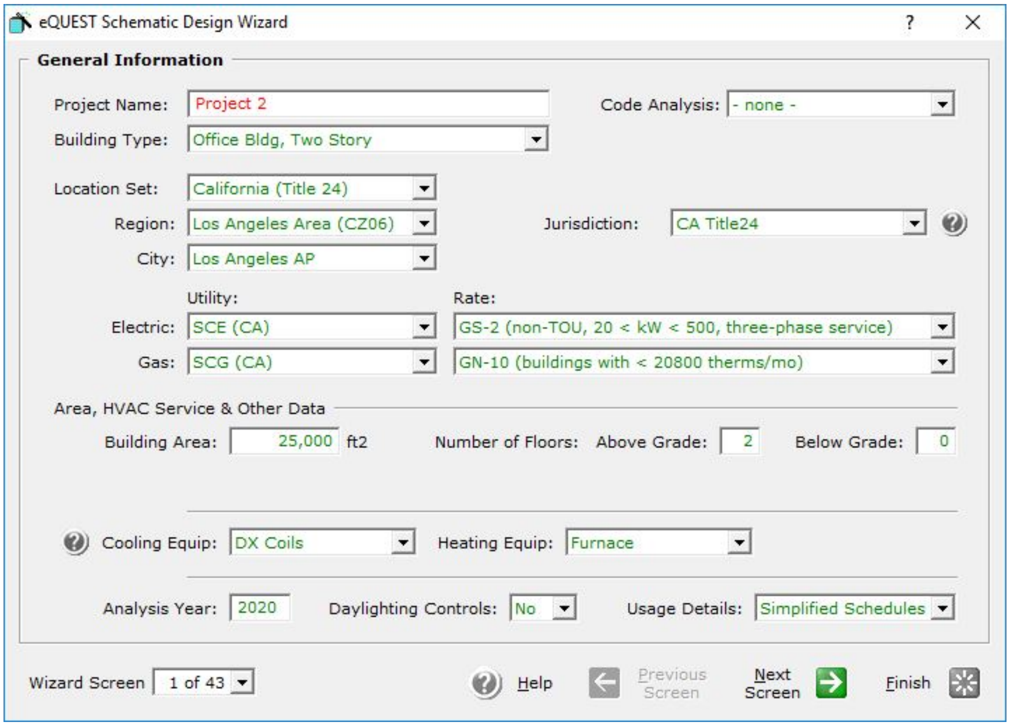


Figure 5-23 eQuest color-coding the inputs with green representing the default values and red representing user inputs.

5.12. Characteristic - Pre-Design/Ideation Themes

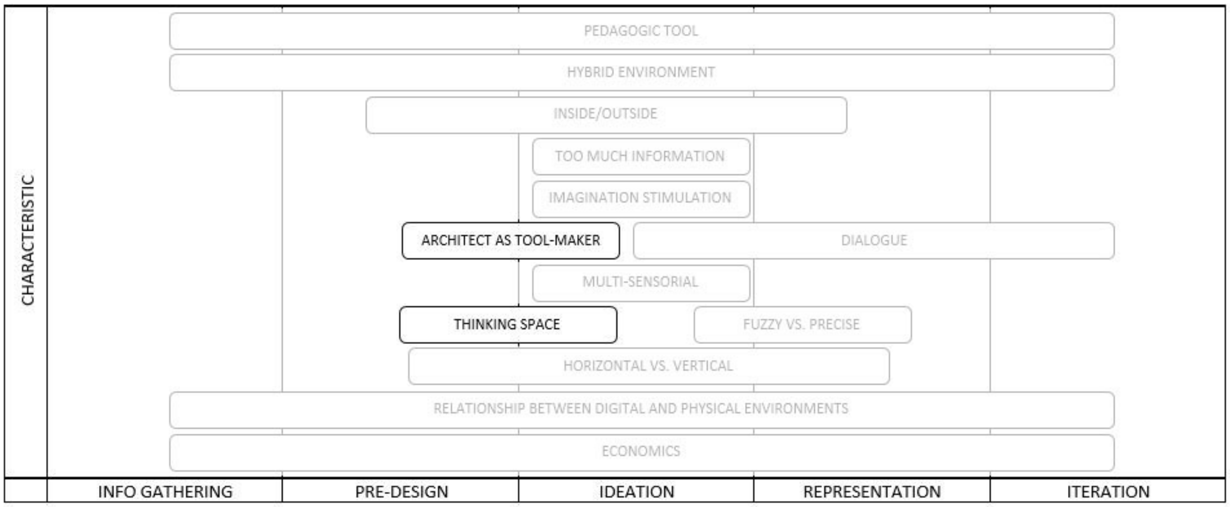


Figure 5-24 Characteristic - Pre-Design/Ideation Themes

5.12.1. Thinking Space

While developing my initial 3D model using SketchUp, I have noted using a very limited set of simple commands, most notably *push/pull* and *move/copy*. I would suggest that using a limited number of simple commands results in quickly mastering them and therefore their use becomes second nature (procedural knowledge). As a result, the architect's mind is free for ideation and imaginative thinking while working on the 3D model. Similarly, Al-Rqaibat, investigating the possibility of hand sketching in digital design environments argues that: "[wrong input methods, complex interfaces, and the need to use a large Palette of commands] shift the focus of the design process from ideation to modeling and representation and may hinder design creativity." (2019, p. 252)

I would suggest that expanding the *tape measure* command and adding more guideline-drawing capabilities would enhance this aspect of SketchUp. I have compared using the tape measure command to sketching with a pencil and creating a layout before using a pen to draw over that layout. I have suggested that the tape measure command appropriately uses dash lines that seem fuzzier (refer to Fuzzy versus Precise) and therefore by using various kinds of lines, the architect is able to document his/her thought process. In its current form, the *tape measure* command is also a limit to design thinking as the geometry of design proposals tends to be limited by the tool.

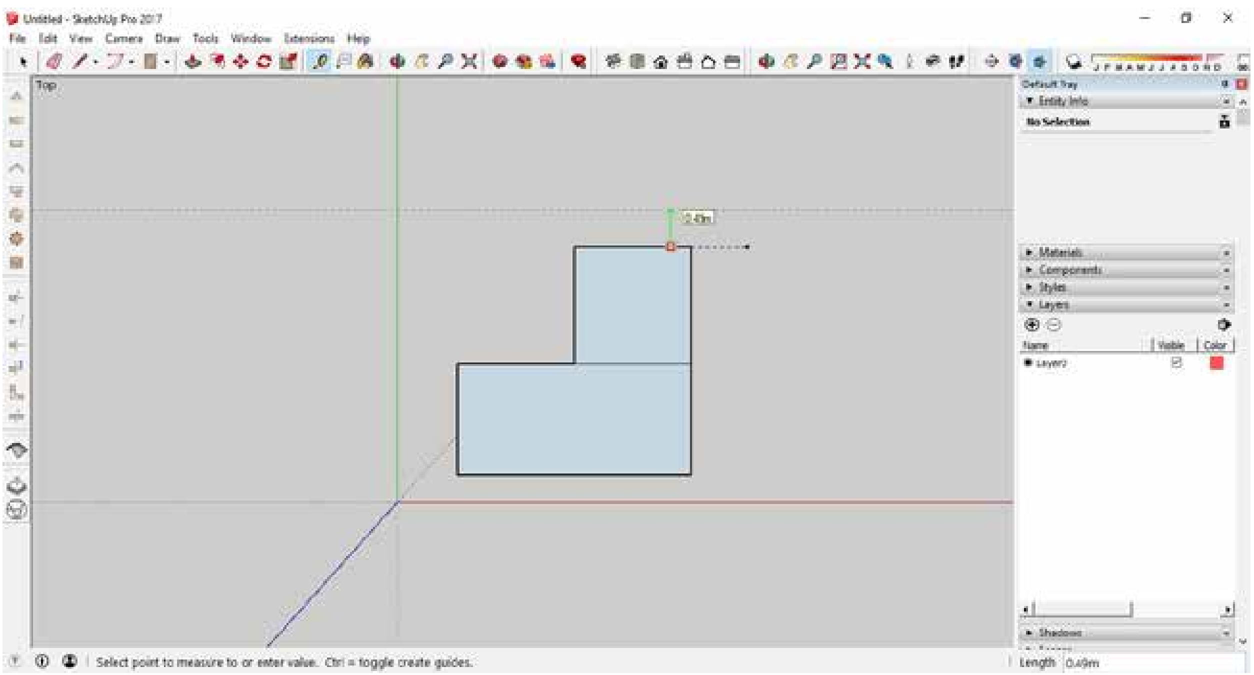


Figure 5-25 SketchUp Tape Measure Command

5.12.2. Architect as Toolmaker and Design Environment Coordinator

In the literature review and interview chapters, I proposed that the architect should be a toolmaker. The proposition does not necessarily mean that the architect or the architecture community would be developing tools such as computer software, but rather it means that the architect, in order to define the design problem, puts together a constellation of tools.

SketchUp Extension Warehouse is a good example of this organized environment. (Figure 5-26) This tool provides a simple procedure for the architect to modify the design environment and add features that help to see the project through a different lens.

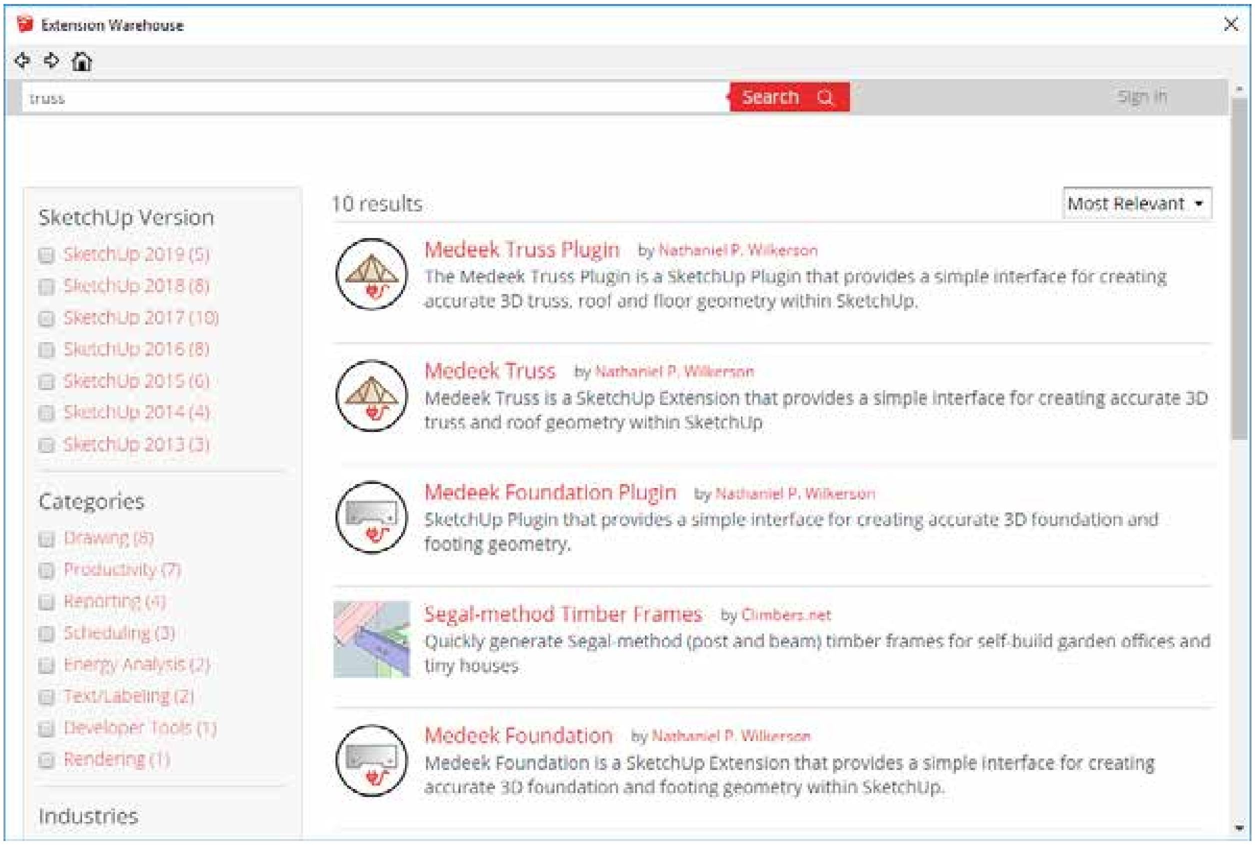


Figure 5-26 SketchUp Extension Warehouse

For instance, fairly early in the design process, I pictured the roof structure as a truss system. Using Extension Warehouse, I searched for “truss” and downloaded the Medeek Truss plugin (Figure 5-27), which helps the user to model truss systems through a graphical user interface. By using the plugin, I was able to quickly study various designs for the truss system enabling me to quickly decide on the appropriate geometry.

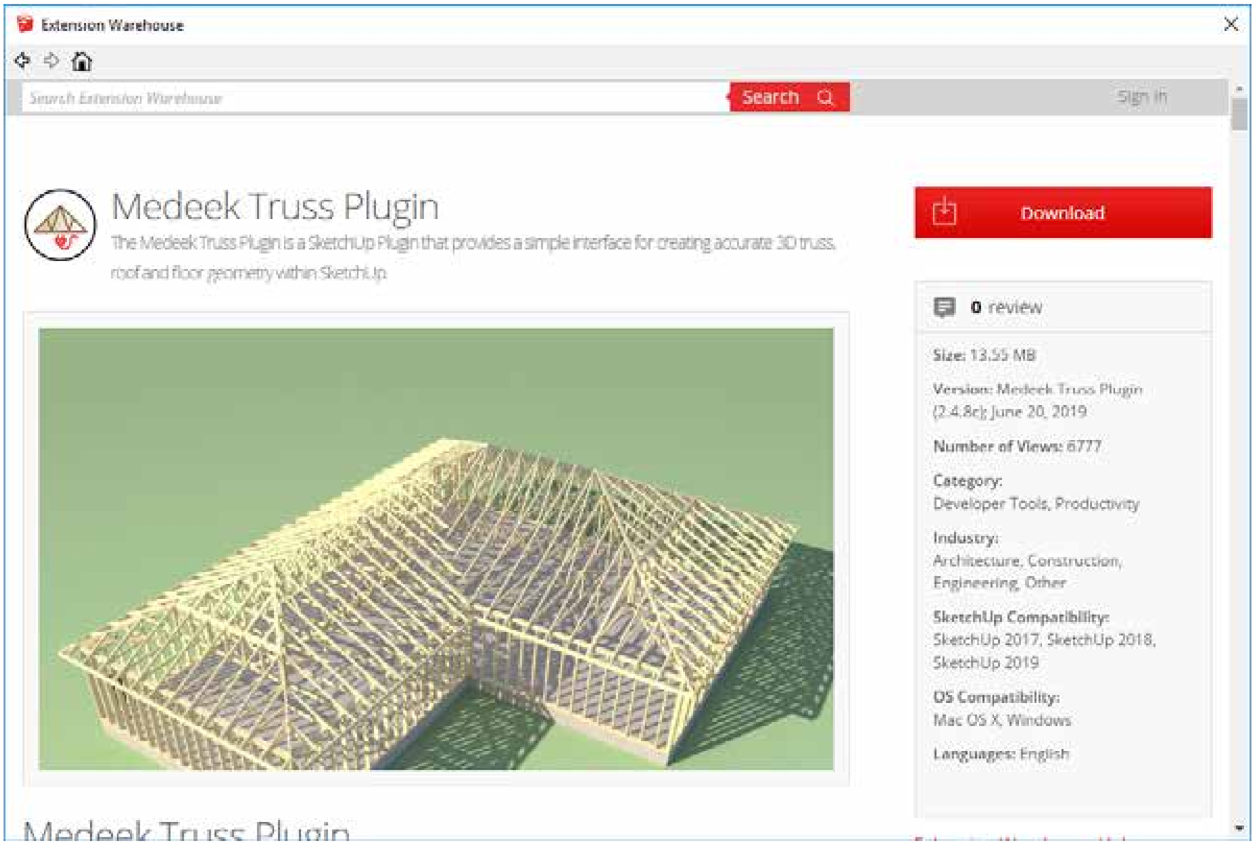


Figure 5-27 Medeek Truss Plugin is SketchUp Extension Warehouse

5.13. Characteristic - Ideation/Representation Themes

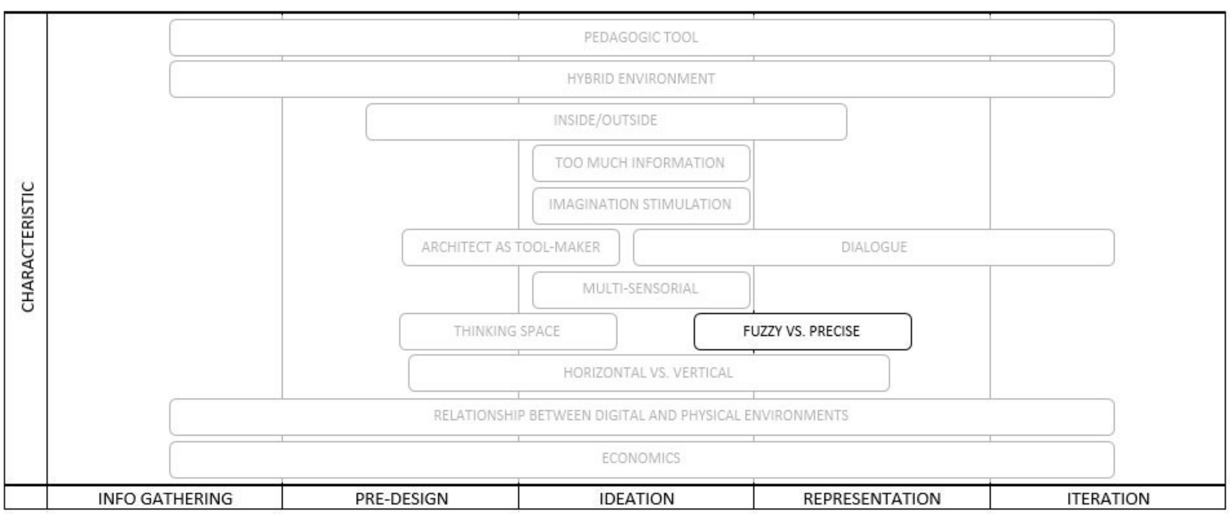


Figure 5-28 Characteristic - Ideation/Representation Themes

5.13.1. Fuzzy versus Precise

Drawing the initial sketch for the design (Figure 5-29), I have noted in my journal: “The pen is more precise and final. At this stage, I like fuzziness which a soft pencil is great for.” (2020) Later, I have noted that I used my pen to draw over the outline first laid out with my pencil. I would suggest that this change of drawing tools and materials (each with its unique characteristics such as color or thickness) associates with layers of information. And in turn, these layers of information make the sketch more meaningful (containing more information) and more readable.

This process of moving from fuzzy to precise through sketching mirrors my thought process; starting with a fuzzy idea and moving toward a clearer and more precise version. It also shows my iterations between the ideation and representation.

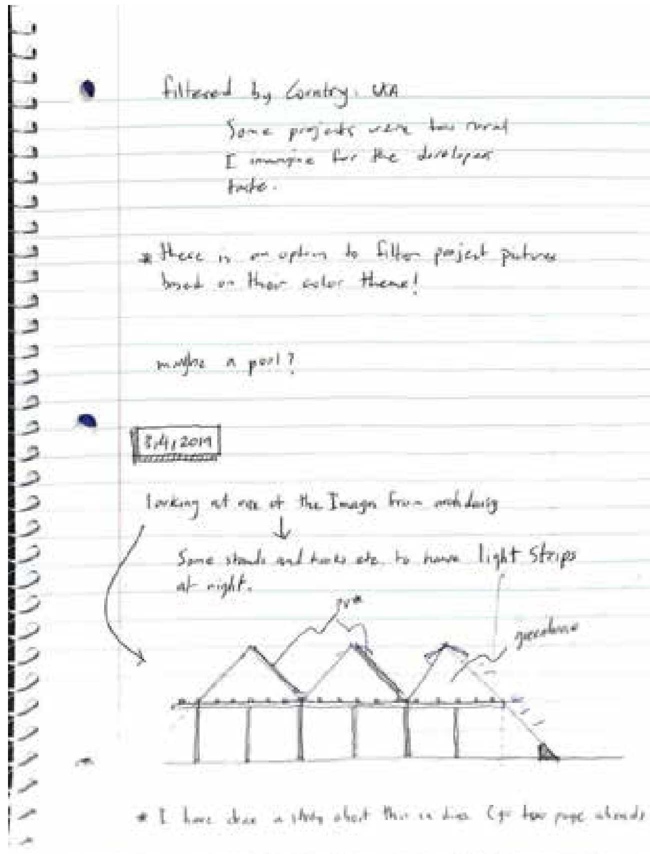


Figure 5-29 Initial Sketch of the Design

I have documented in my journal that features such as Styles in SketchUp (Figure 5-30) are useful to imitate the fuzziness of a hand sketch during the early stages of the design process. However, it is not as intuitive as a hand sketch and it remains a conscious act of representation. In other words, even though the final results might look like each other, but the cognitive process that the architect goes through while drawing a fuzzy hand sketch and applying a fuzzy sketch Style to a SketchUp model is different. I never use these Styles while I am creating the 3D model, I only apply them to give the right feeling to my drawing before exporting an image. So, this fuzziness is most useful for communicating with others and not as a dialogue with the designer.

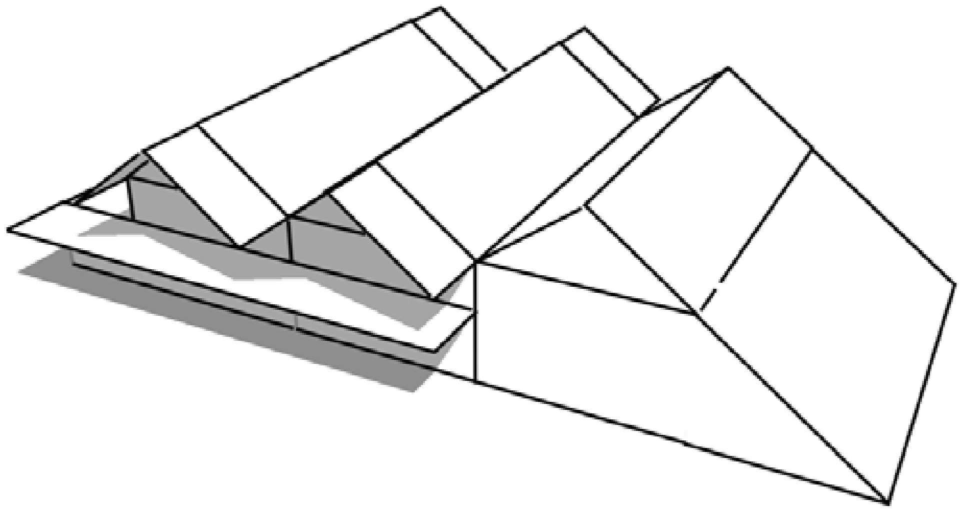


Figure 5-30 A sketch style in SketchUp

5.14. Feature - Ideation/Representation Themes

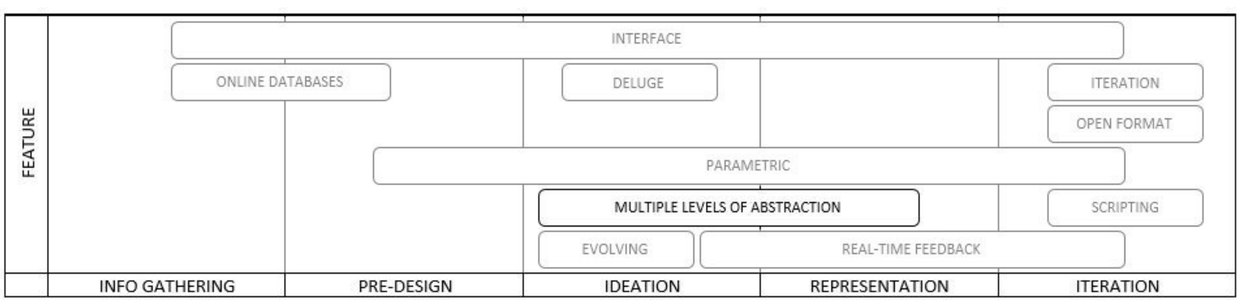


Figure 5-31 Feature - Ideation/Representation Themes

5.14.1. Multiple Levels of Abstraction

I have noted that while drawing the initial massing sketch for the design (Figure 5-29), I found myself suddenly “switched” to thinking about the details of the pergola (the order of the beams, joists, and columns.) Similarly, Cross points out that “[using sketches,] designers think about the overall concept and at the same time think about detailed aspects of the implementation of that concept.” (2006, p. 37) He argues that this feature in sketches “enable[s] designers to *handle different levels of abstraction simultaneously*”. (2006, p. 37)

BIM, similar to sketching, promotes handling different levels of abstraction simultaneously. However, at least the implementation of the concept in tools such as Revit demonstrates important flaws. Comparing hand sketching to Revit illustrates these flaws in two major aspects:

1. While hand sketching supports moving between ideation and representation, Revit remains mostly an environment for representation and connection to construction documentation. In other words, what Cross argues to be a “critical [and] reflective dialogue through sketching” (2006, p. 37) seldom happens in Revit.
2. The Revit interface (both software and hardware) is complex and rigid when compared to hand sketching, which makes it difficult to incorporate in the early stages of the design process.

5.15. Characteristic - Ideation/Representation/Iteration Themes

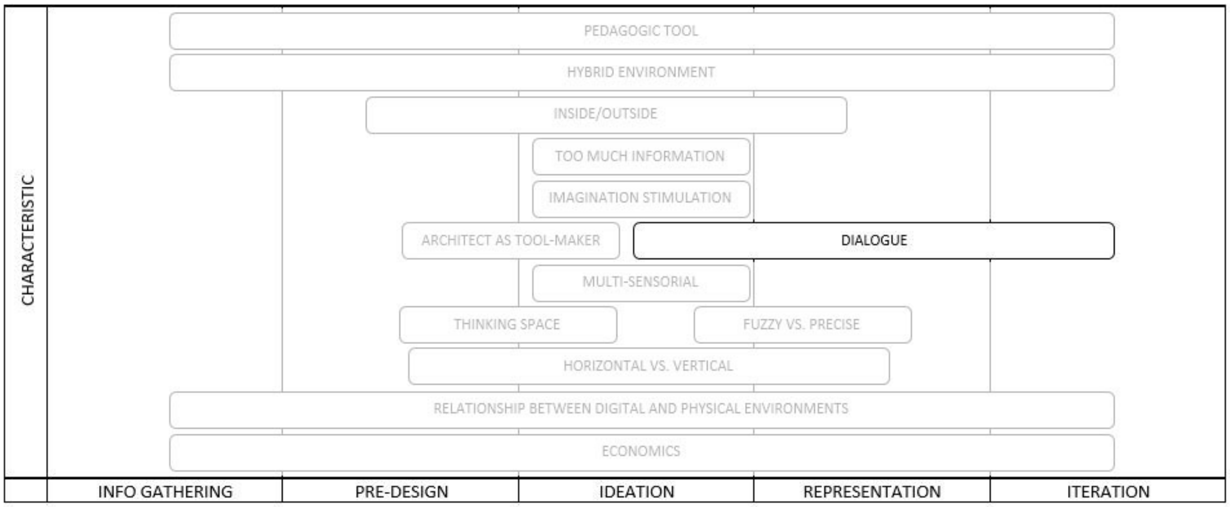


Figure 5-32 Characteristic - Ideation/Representation/Iteration Themes

5.15.1. Dialogue

As previously discussed, the *dialogue* theme is partly concerned with communication between various parties involved in the project. Modelo provides an online discussion and 3D commenting features that enable all members involved in the project to exchange their thoughts and ideas.

Figure 5-33 demonstrates a hypothetical situation in which the designer uses this feature to communicate a question about the structural requirements of an element with the structural engineer in the team. This feature enables the user to choose the most representative view and link the comment to a specific element in that view using labels. Since Modelo is an online platform, various team members can connect from different locations and communicate using this feature.

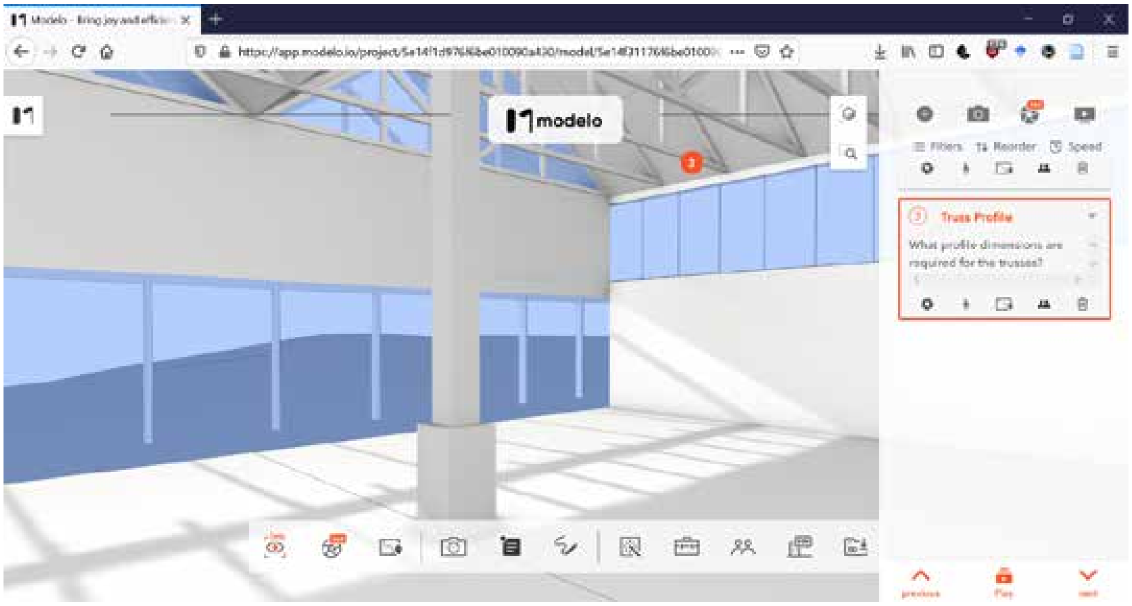


Figure 5-33 Discussion and 3D comments features in Modelo

However, this feature can be further developed by enabling the users to define their roles in the team. (refer to 5.17.1 Audience) Therefore, the users would be able to direct their comments to other users with a certain role or receive comments that are directed to their role.

5.16. Feature - Ideation/Representation/Iteration Themes

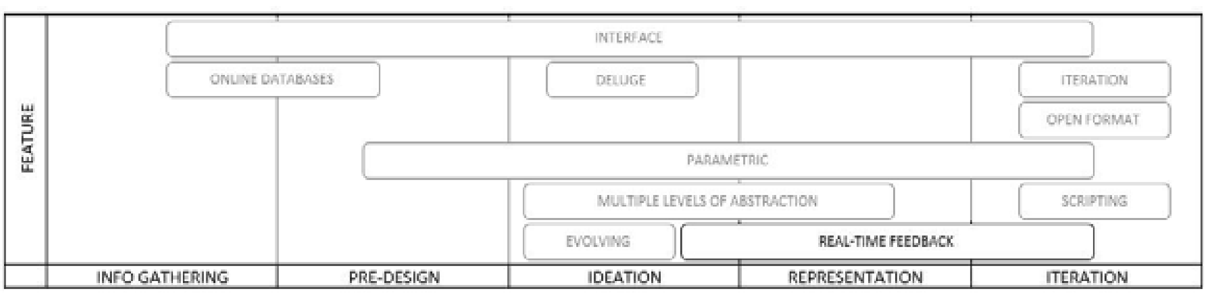


Figure 5-34 Feature - Ideation/Representation/Iteration Themes

5.16.1. Real-time Feedback

During the literature review, I began to envision a working environment (Figure 5-35) that has a built-in daylight analysis module as well as the capability to import images of the site's surroundings to simulate the views. All of this information would be assigned to layers that can be turned on or off by the architect during the design process, giving him/her the ability to focus on certain aspects of the design and while not being overwhelmed with unnecessary information during the early stages of the design process. The incorporation of 3D geospatial information to study the view during the design process has been studied in research by Obeidat (2020). However, this hypothetical working environment extends his suggestions by incorporating other layers of quantitative information.

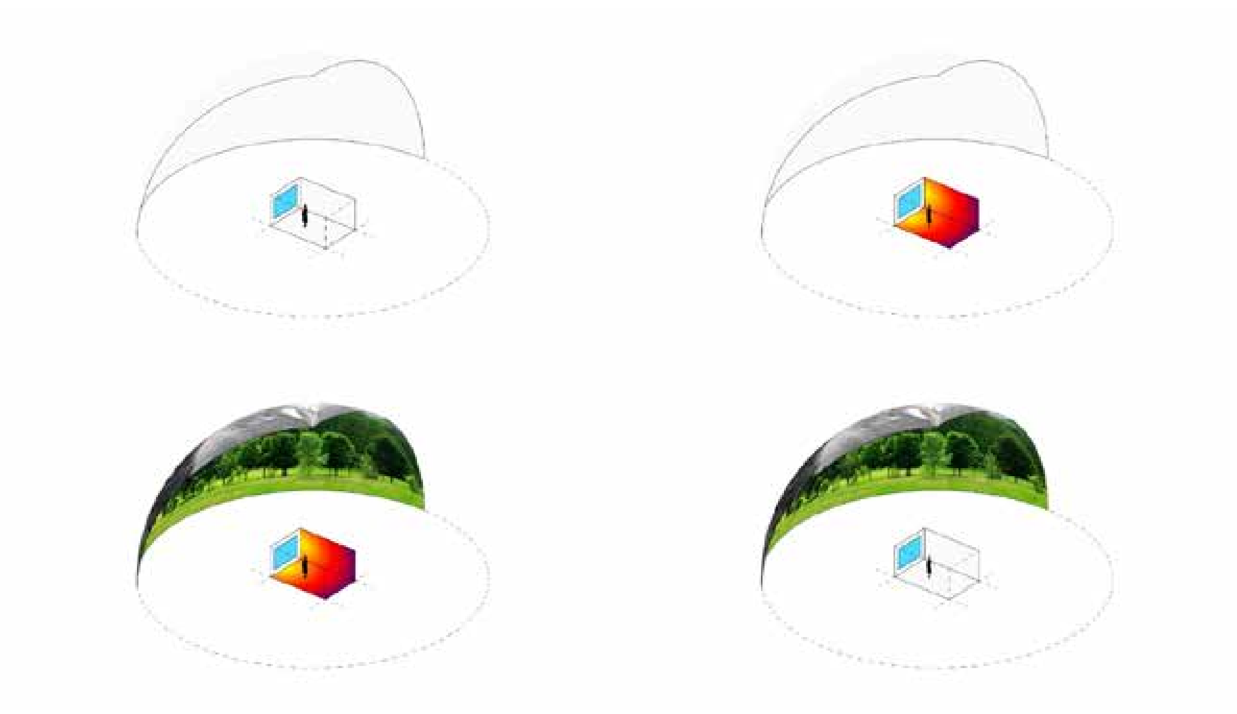


Figure 5-35 A hypothetical working environment with built-in daylight and view simulation capabilities.

As part of the immersive case study, I was interested in experimenting with this idea. There seem to be at least two areas of development for importing graphical representation of the surrounding environment. The first is the development of 360-degree cameras. Virtual reality engines such as Unity or rendering engines such as Lumion have features to import these 360 images and use them as a background for an imported 3D model. However, this method is not useful for the representation of objects which are in close proximity to the site. Moreover, at the early stages of development, the process of exporting the model to, for instance, Unity, and adding these layers of information is relatively complex and time-consuming, making it less likely to be used.

The other suggested area of development is to create a textured 3D model of the surrounding environment which is usually done in one of three different methods:

1. Using photogrammetry at a local scale, a drone takes many images of the surrounding environment from various angles. These images are later used to create a 3D model and texture it using software such as RealityCapture. Although the hardware and software for this are becoming more accessible, the process is still relatively complex and time-consuming.
2. Using photogrammetry on a global scale, services such as Google Earth take millions of images of the earth from various angles using satellites and airplanes. These images are later used to create a textured 3D model of large areas of the earth's surface. (Figure 5-36) These models are not yet available publicly outside Google's own platform.
3. Gathering 3D models created by users, through services such as Open Street Map which have a database of publicly available 3D models of some urban areas. (Figure

5-37) However, the availability, quality, and accuracy of these models can vary from one area to another.

Figure 5-36 Google Earth 3D view of New York City accessed through Google Maps

Figure 5-37 Open Street Map's 3D view of New York City accessed through osmbuildings.org

There are plugins developed for 3D modeling environments to simplify some of these complex and time-consuming procedures. For instance, Oob Terrain, a plugin for SketchUp, enables the user to import the site's terrain, texture, and surrounding buildings from Google Earth, Open Street Map, and other databases with only a few clicks. (Figure 5-38)

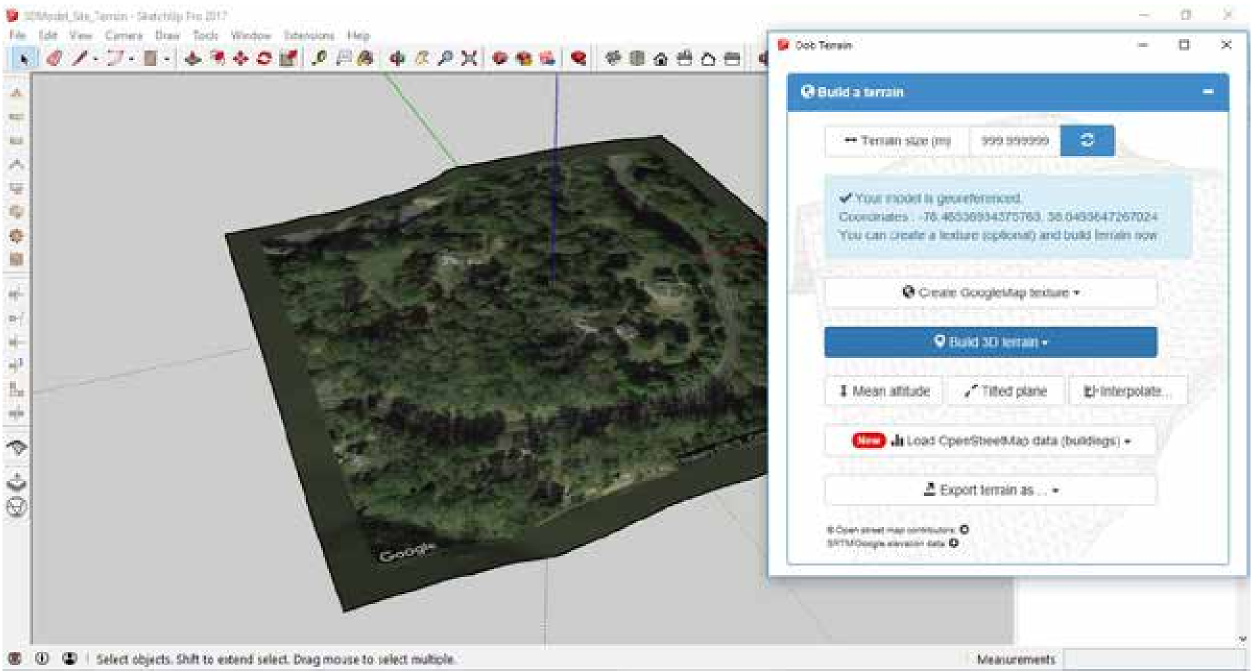


Figure 5-38 Oob Terrain in SketchUp

When considering the quantitative aspects of decision-making, the daylighting screen in CoveTool provides an interesting, interactive way to study the effect of openings size and shading on the intensity of the daylight inside the space. (Figure 5-39) However, I would suggest that the simplistic interface of CoveTool makes it only applicable for rectilinear designs.

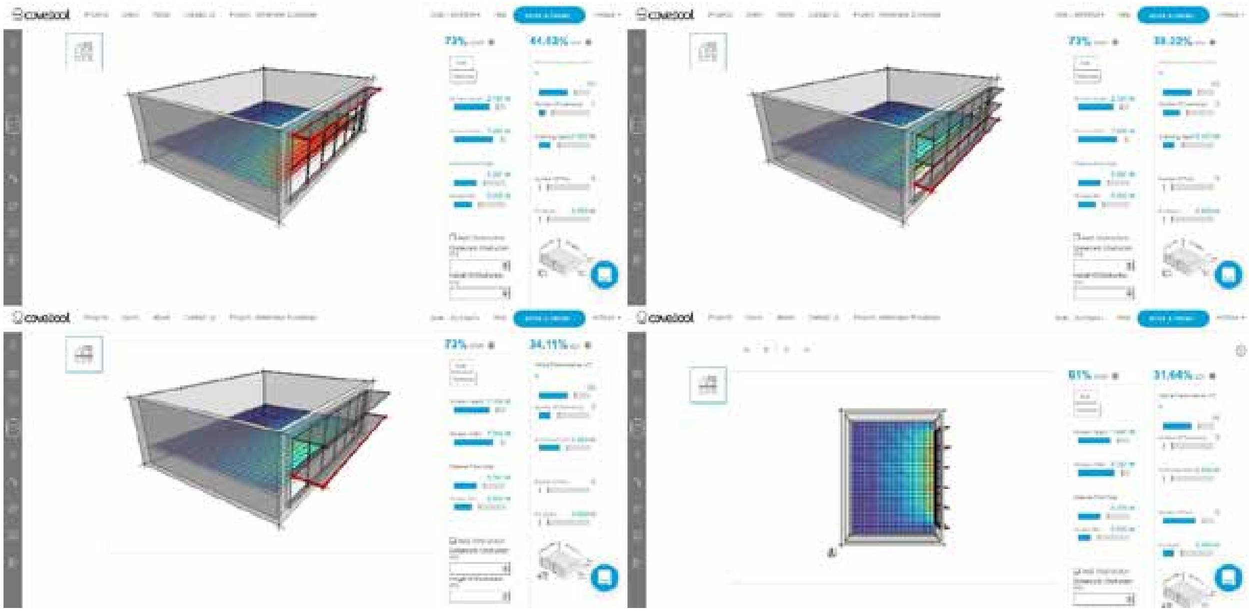


Figure 5-39 CoveTool's daylight analysis screen

An important area of development for the *real-time feedback* theme is the application of Virtual Reality (VR) and Augmented Reality (AR) tools. Campbell and Wells state that “non-immersion [in a virtual environment] offered easier and quicker manipulation of the viewpoint” (1994, p. 5) which they argue is a helpful feature for studying the exterior of the design. On the other hand, an immersive virtual environment supports studying interior spaces, especially details and connections. This aspect is mentioned in a more recent study by Schnabel and Kvan who suggest that immersive virtual environments “maintain the feeling of presence within the models thus enhancing the exploration of space, volume and location.” (2003, p. 445)

Gaming engines such as Unity provide many features to represent architectural spaces. However, currently, the complexity of these gaming engine environments limits their use in architectural applications. I have documented in my journal that the process of preparing a Rhino model and exporting it to Unity took about two hours which is a considerable interruption in the ideation/representation/iteration process for the early stages of the design.

Some tools have tried to improve this process. For example, Modelo.io is an online service advertising itself as "design review software for architects." (*Modelo*, n.d.) It enables the user to upload a 3D model in several formats including Rhino, Revit, and SketchUp, and view it using mobile VR headsets such as Google Cardboard. (Figure 5-40)

Figure 5-40 Modelo and Google Cardboard VR headset

This reduced the transition process to a couple of minutes which is more practical for the early stages of the design process. Being an online service, Modelo does not require the user to install any new applications. This helps to limit problems related to interoperability. (Figure 5-41) However, I noted that services such as this need to be better integrated into the 3D modeling environment, to enable the architect to switch back and forth between designing, modeling, and reviewing the model in VR. This suggests that developers of Modelo should consider a plugin for 3D modeling environments such as Rhino.

Figure 5-41 Modelo rendering the model for VR headsets in a mobile phone browser

I also noted that the *Position Camera* command in SketchUp (which by default gives an eye height view from the selected position) is a useful tool for getting qualitative real-time feedback. (Figure 5-42) In other 3D modeling environments such as Rhino, although one can modify the camera to imitate this command, there is not a single dedicated command, resulting in camera views being delayed until the production of renders later in the design process. This feature is also important for tools such as Modelo which are concerned with this feedback.

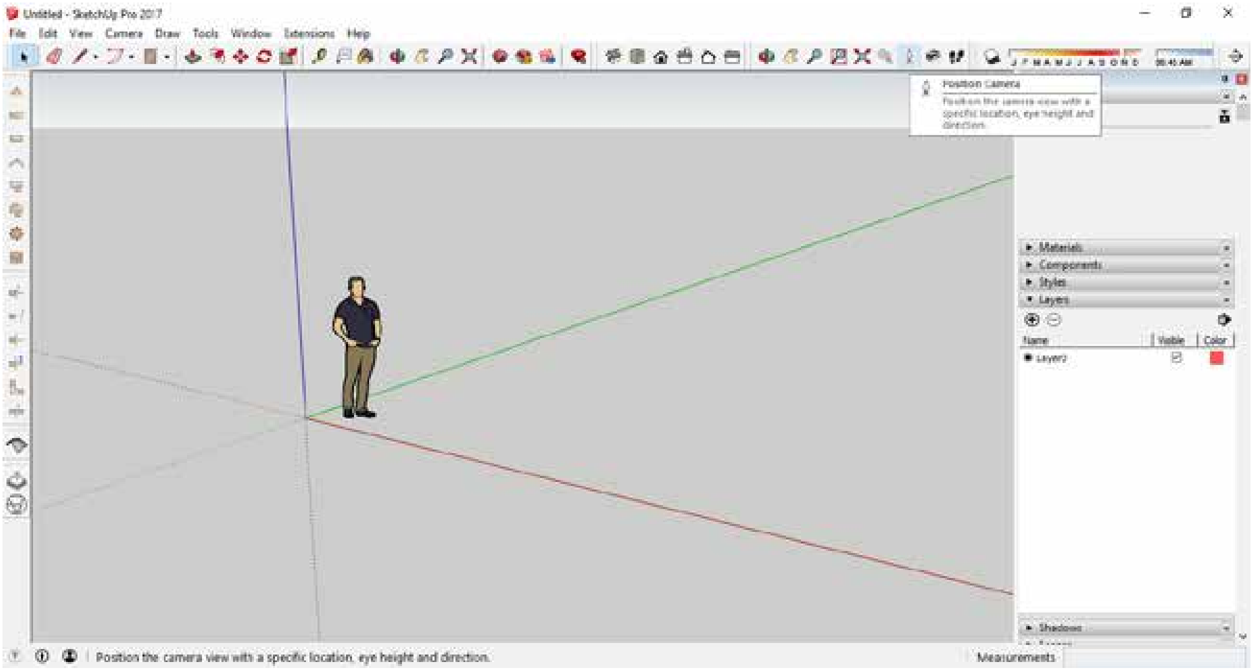


Figure 5-42 SketchUp Position Camera command

5.17. Knowledge - Info Gathering/Pre-Design/Ideation/Representation Themes

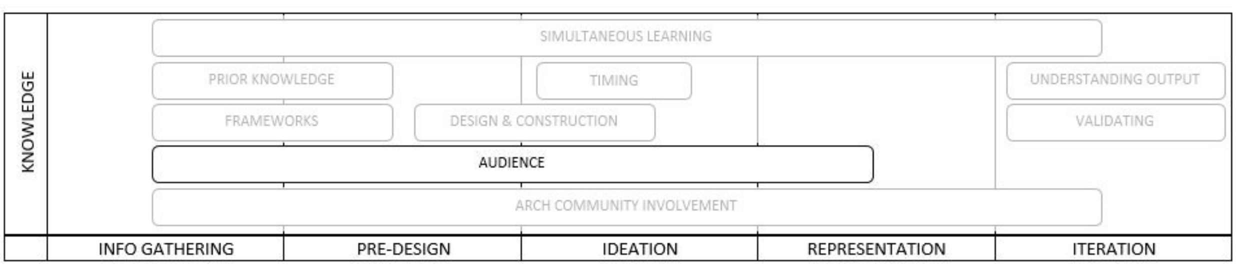


Figure 5-43 Knowledge - Info Gathering/Pre-Design/Ideation/Representation Themes

5.17.1. Audience

A good example of a tool that addresses the need to connect various audiences and their different knowledge domains is CoveTool. CoveTool provides the user with the option to choose his/her role as part of the design team (architect, mechanical engineer, owner, and contractor) while working within the CoveTool environment. (Figure 5-44) Currently, this feature is not fully developed. However, in the future, it can customize inputs, reports, or even the interface based on the role of the user. For instance, if the user would choose "owner" as his/her role, the interface would become less complex and focus mostly on the reports section, presenting results for different alternative design strategies.

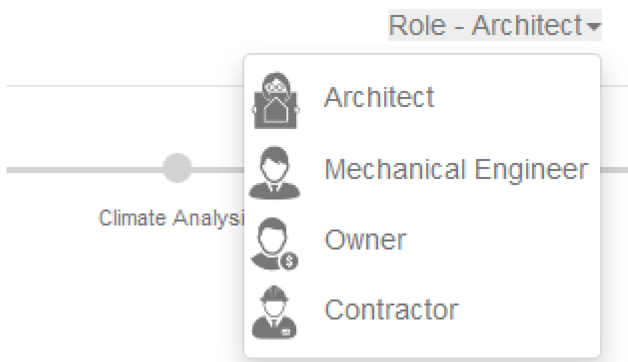


Figure 5-44 Role selection feature in CoveTool

This suggests that different parties in a design project have different knowledge domains and concerns that require diverse ways to support interaction and representation. By acknowledging this and incorporating features such as the *role selection option* in CoveTool, the tool becomes a platform to support the dialogue between these various parties.

5.18. Knowledge - All Stages Themes

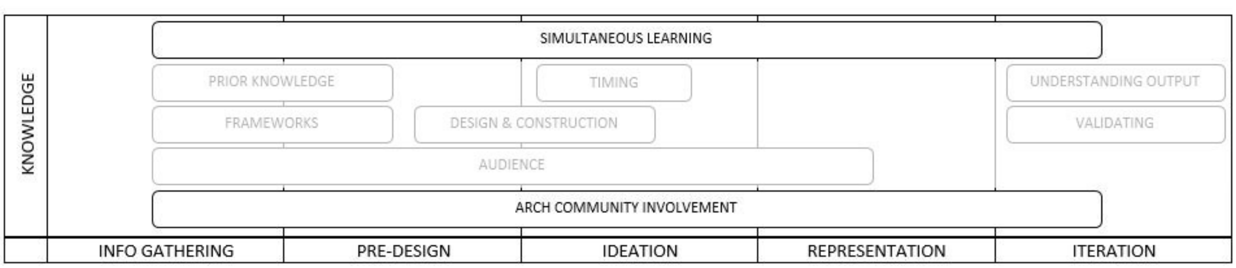


Figure 5-45 Knowledge - All Stages Themes

5.18.1. Architecture Community Involvement

I have discussed Climate Consultant in the context of the *pedagogic tool*, *timing*, and *framework* themes. Because this tool was developed by the Department of Architecture and Urban Design at the University of California, Los Angeles (UCLA) it is an example of how the architecture community can contribute to the development of new digital tools.

The comparison between Google Images and ArchDaily (as discussed in section Online Databases) is another good example of the benefits of a tool (ArchDaily, an online database) developed directly by the architecture community. ArchDaily shows how this involvement translates into features and characteristics that are tailored for architects and their workflow.

5.19. Cognition - All Stages Themes

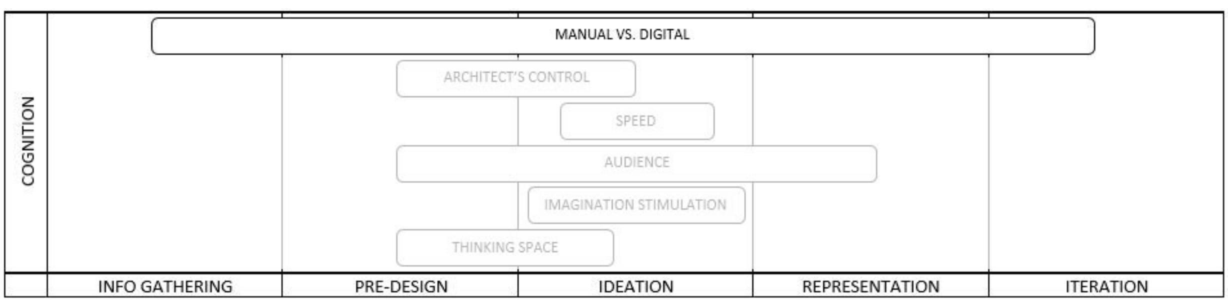


Figure 5-46 Cognition - All Stages Themes

5.19.1. Manual versus Digital Differences

I have noted that while working with a physical model, the interactions with specific materials allow me to comprehend various components in relation to one another. While working with a digital 3D model, on the other hand, this relation does not happen intuitively and needs to be done using my imagination and through a meta-cognitive act. For instance, I have noted that while working on the physical model I was able to put a piece where it is supposed to be in the model, move it or rotate it to achieve the form I am looking for, mark it, and then cut it to size. Or, using a wood saw to cut the wood profile, I was able to use the saw as a mirror to reproduce the connection of one piece to the other, adjust the angle, and then make the cut. (Figure 5-47)

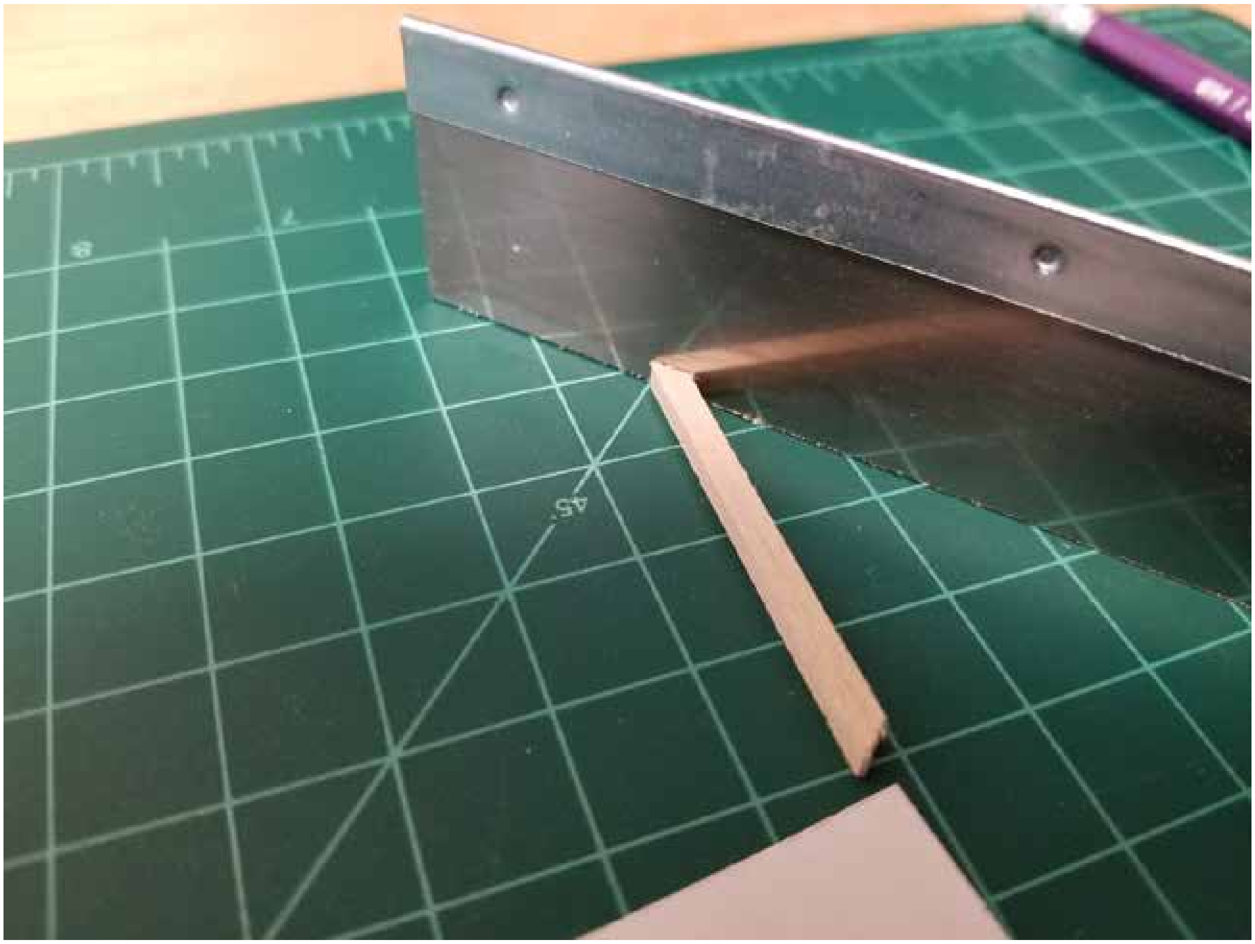


Figure 5-47 Adjusting the cut angle using the saw body as a mirror

This suggests that, cognitively, there is a difference between manipulation of physical objects and manipulation of virtual objects in a digital 3D environment. It is suggested that manipulation of physical objects is more supportive of design thinking at the early stages of the design process. (Kim & Maher, 2008) This can help to explain several architects' choice, including

Frank Gehry and Thom Mayne, to start with physical models and then move to digital 3D models by scanning the emerging physical model. (Pollack, 2006)

5.20. Characteristic - All Stages Themes

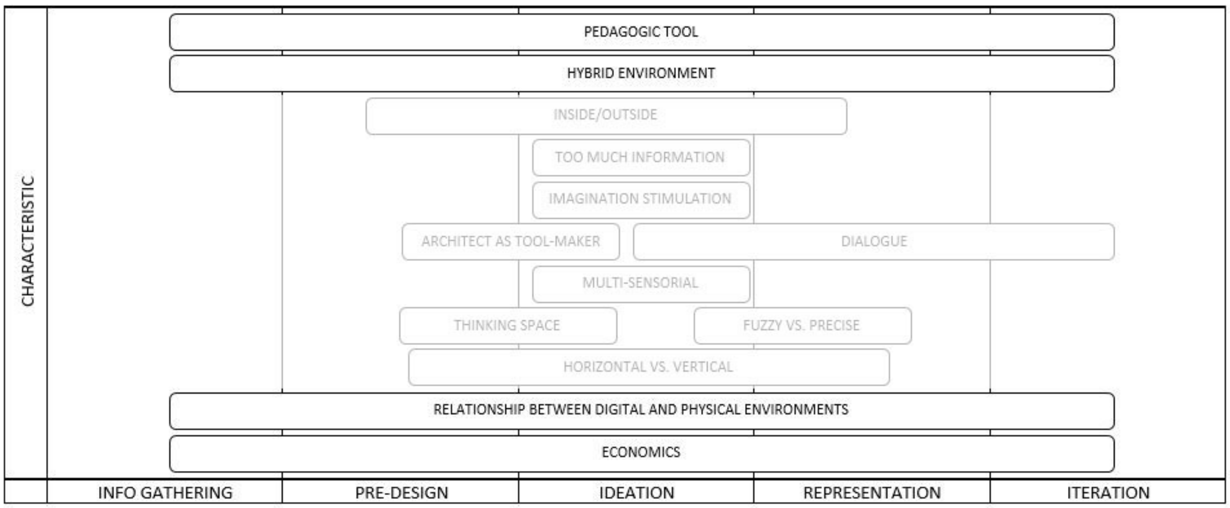


Figure 5-48 Characteristic - All Stages Themes

5.20.1. Pedagogic Tool

One investigation that I performed during the immersive case study was a shadow study using Diva. (Figure 5-49)

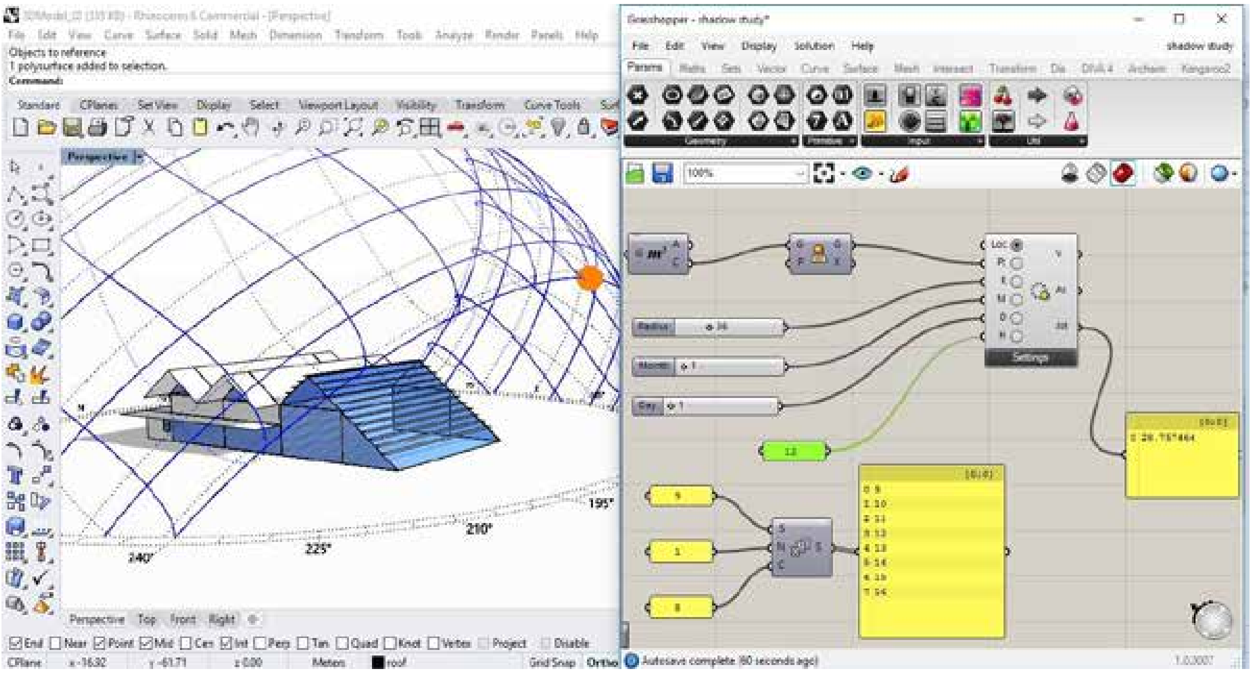


Figure 5-49 Shadow Study

I have noted that the shadow study was intended to help me visualize the sun's daily, monthly, and yearly movement in relation to my design proposal. This is an example of a pedagogic investigation since it provides me with the knowledge that may be useful in future projects. I have noted certain characteristics in Diva which I believe support this pedagogic aspect:

1. The parametric capabilities
2. The instant feedback

By using the Grasshopper graphic scripting interface, Diva enables the user to have a clear view of the inputs and the flow of the information. Also, since Grasshopper runs on a separate window than Rhino, the user can run these two windows next to each other (Figure 5-49) and get instant feedback in Rhino by modifying the inputs in Grasshopper. This package transforms the investigation from one that is only relevant to a specific project to one that more generally represents the process.

Similarly, the Medeek Truss plugin for SketchUp is an example of an educational tool that demonstrates the same two characteristics. (Figure 5-50) Here again, the parametric and instant feedback capabilities enable the user to study the effect of changing parameters related to the truss system.

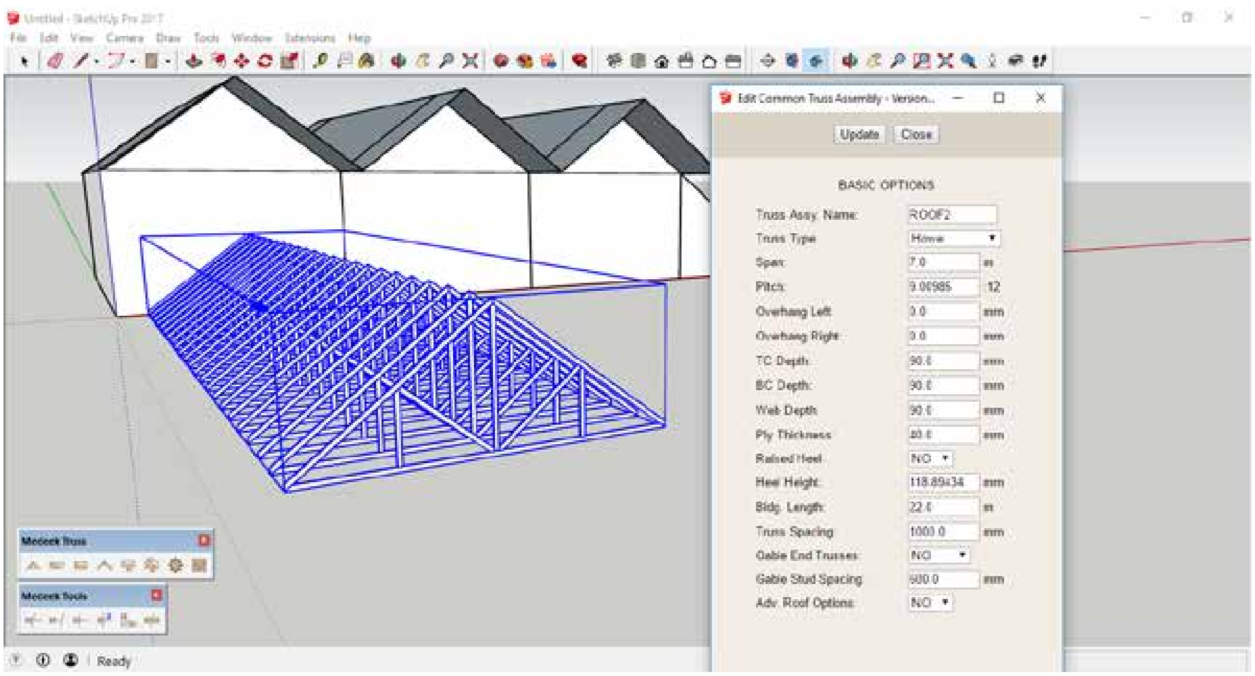


Figure 5-50 Medeek Truss plugin for SketchUp

Moreover, in the Medeek Truss plugin selection screen (Figure 5-51) not only is the user providing the needed input, but the schematic sketches for each truss type educate the user about various truss design geometries. Even if the user would not consider all of these truss types for the current project, this approach allows him/her to consider these options in future projects.

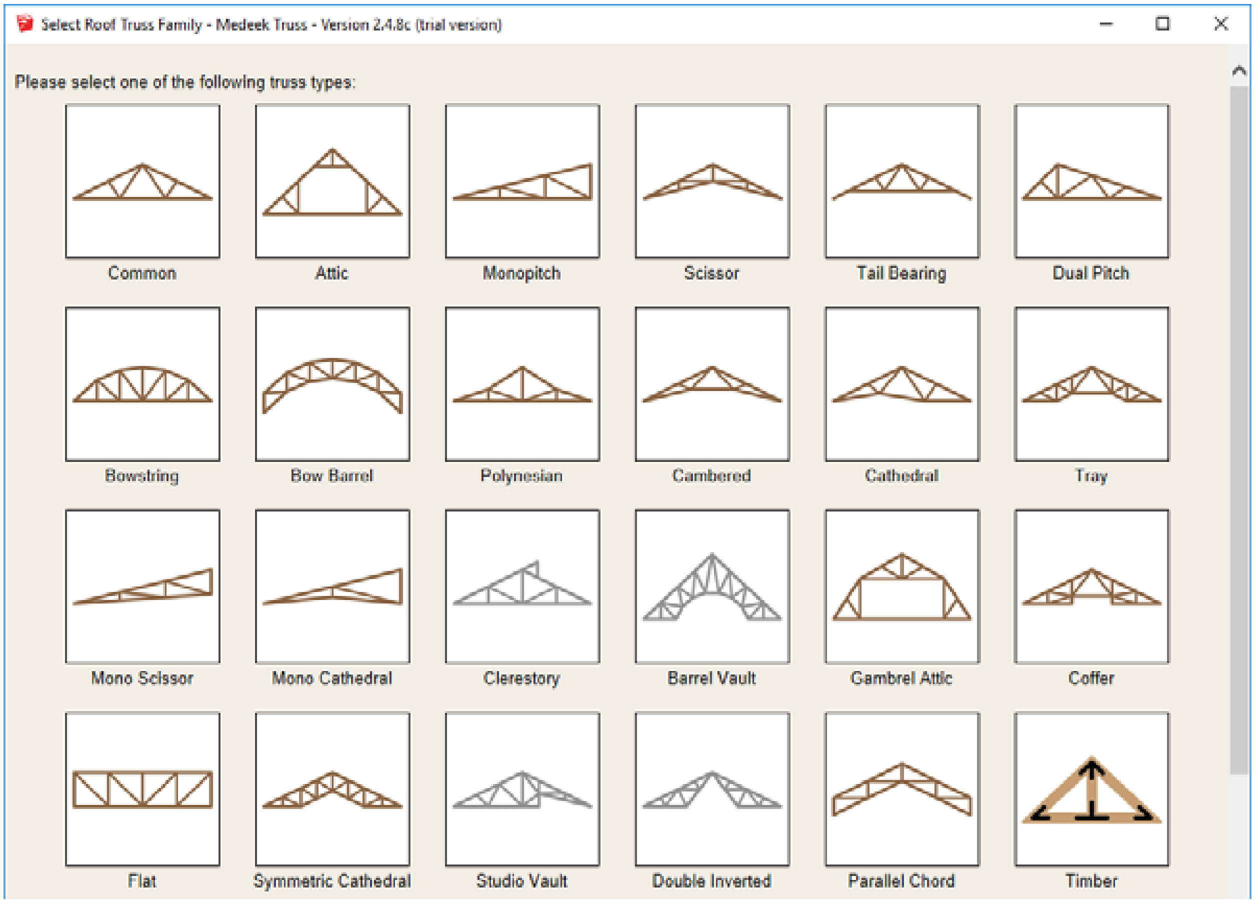


Figure 5-51 Medeek Truss plugin Truss Type Selection Screen

SketchUp has a feature similar to Diva to study the dynamics of shadows. (Figure 5-52) However, what makes Diva more educational, is the incorporation of the sun path diagram in the representation. By doing so, Diva creates a mental link between the objectives of the study and results, and the *a priori* knowledge that the architect has acquired through his/her education.

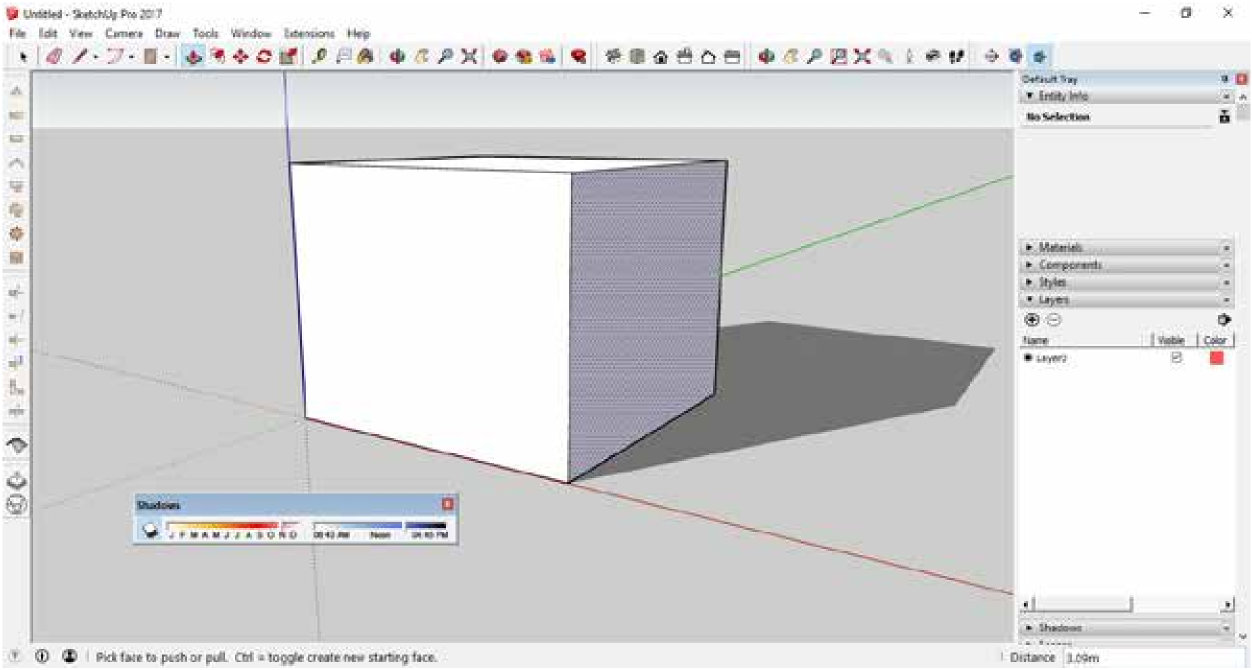


Figure 5-52 SketchUp Shadow Feature

Climate Consultant is another example of a pedagogic tool. This tool provides graphical representations, diagrams, and design guidelines based on local weather data. It is clear that the tool is not developed merely to perform a task but also to educate the user about issues related to the influence of climate on design. For instance, The Comfort Model wizard (Figure 5-53) not only lets the user choose between available comfort criteria, but also educates the user about the differences between those criteria.

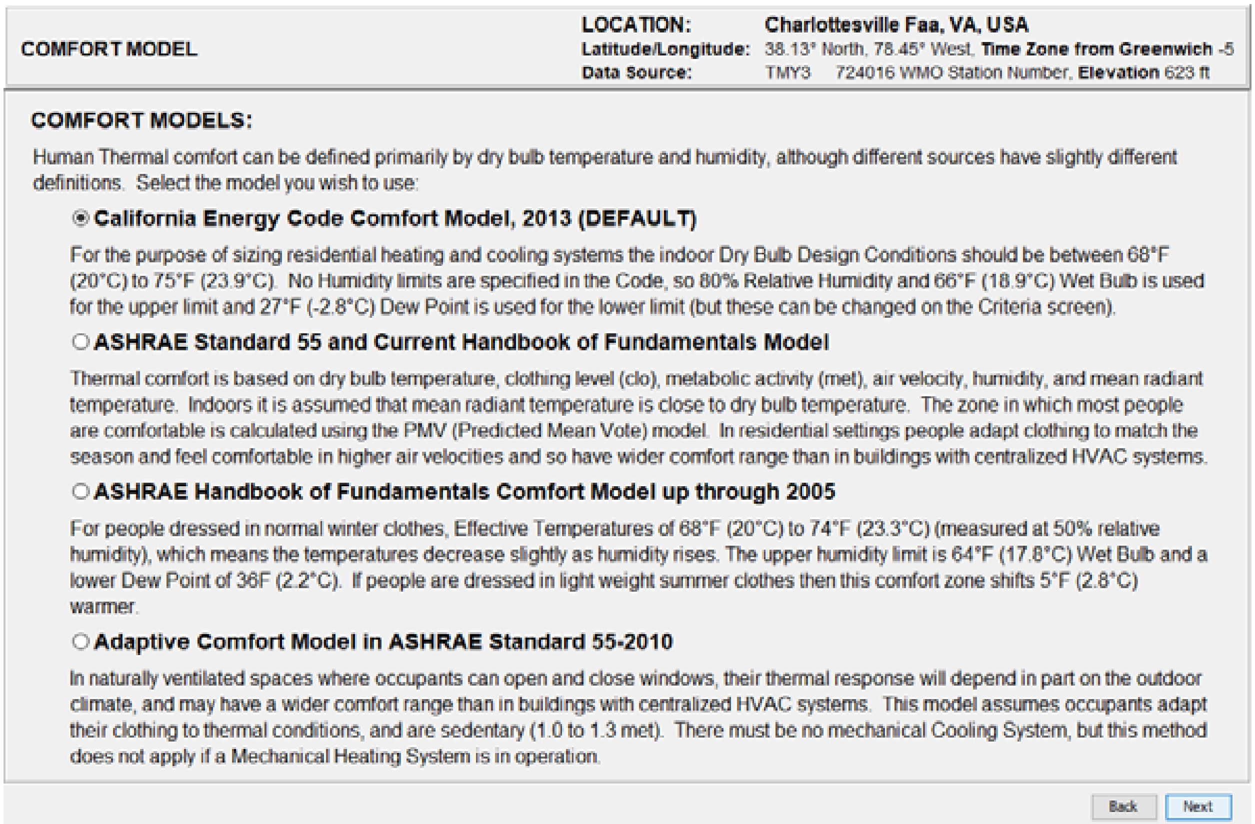


Figure 5-53 Climate Consultant Comfort Model Wizard

For Climate Consultant, the most informative part of the program is the Design Guidelines wizard. This wizard suggests design strategies (Figure 5-54) based on user input. (Figure 5-56) The design guidelines illustrate how quantitative information derived from climatological data can inform the design process in the very early stages. This is an important feature that is missing in the Diva glare analysis. I have noted in my journal that it would be useful and educational if Diva were able to provide recommendations and design guidelines based on the results of the glare analysis. (Figure 5-55)

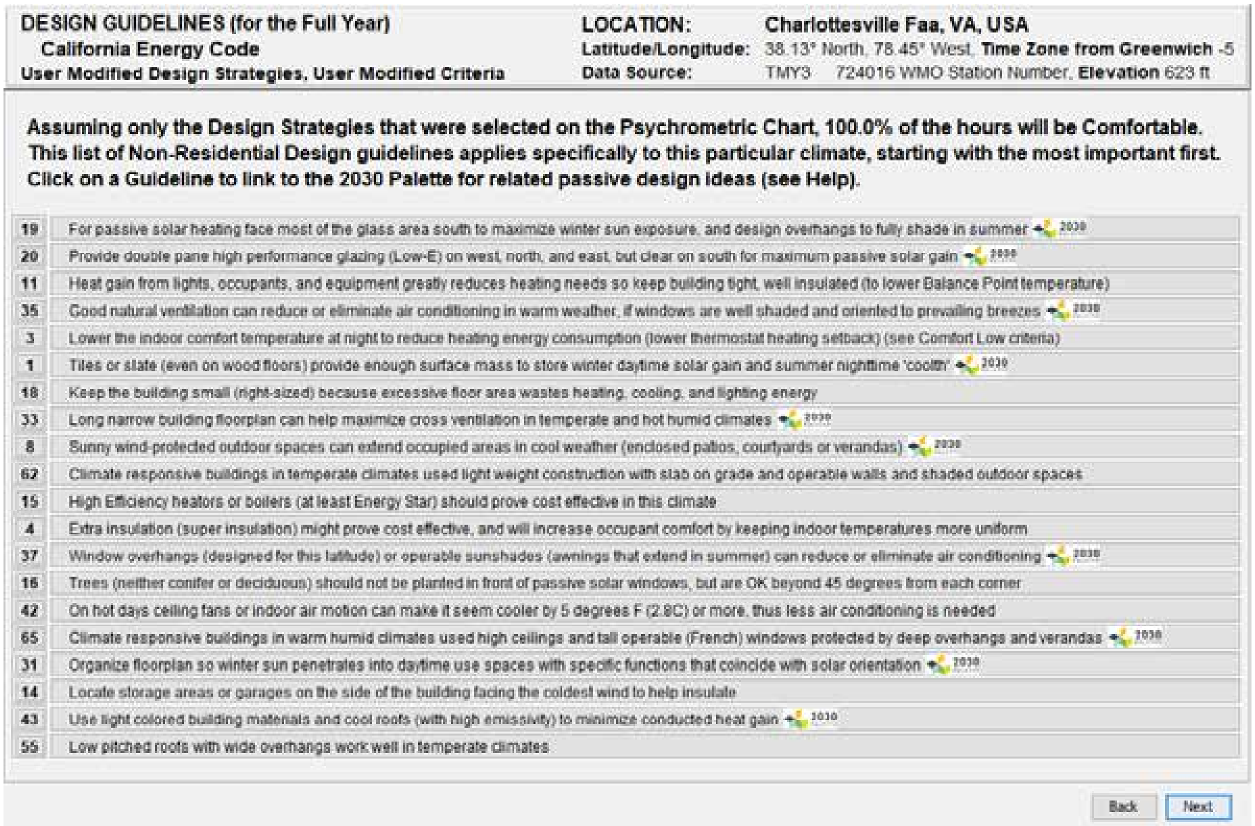


Figure 5-54 Climate Consultant Design Guidelines Wizard

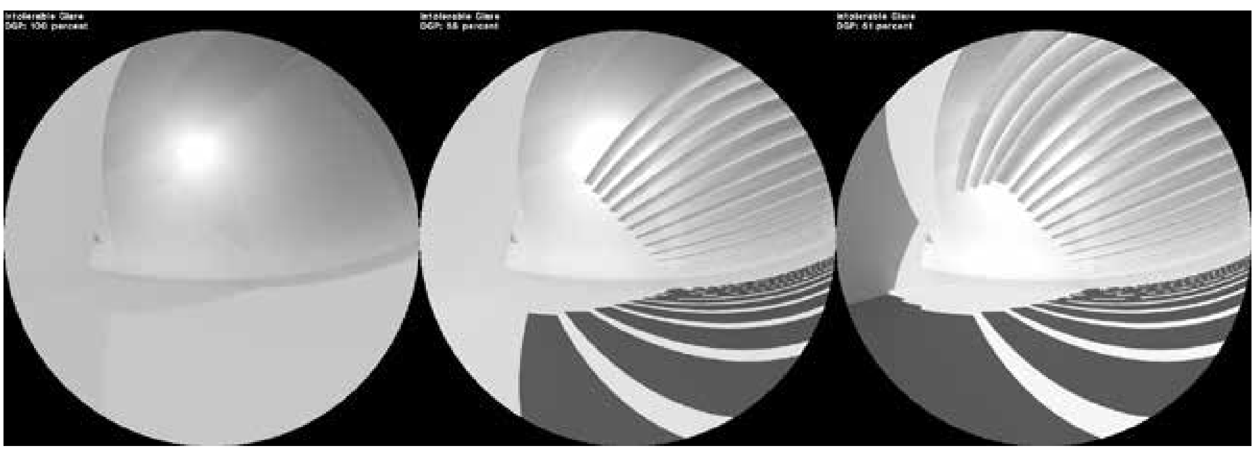


Figure 5-55 Glare analysis using Diva for the greenhouse

Similar to the shadow generation component in Diva, Climate Consultant elevates the tool to be educational by linking the process to *a priori* knowledge that architects have acquired during their education (the use of the Psychrometric chart).

Also, not only does Climate Consultant provide simple sketches that illustrate the design guidelines (Figure 5-57), making them easier to understanding for users with less experience, they also refer to other resources (the online 2030Palette database) for further reading. Consequently, the tool provides a map, guiding the user while allowing the user to decide how deep he/she wants to go related to a certain guideline.

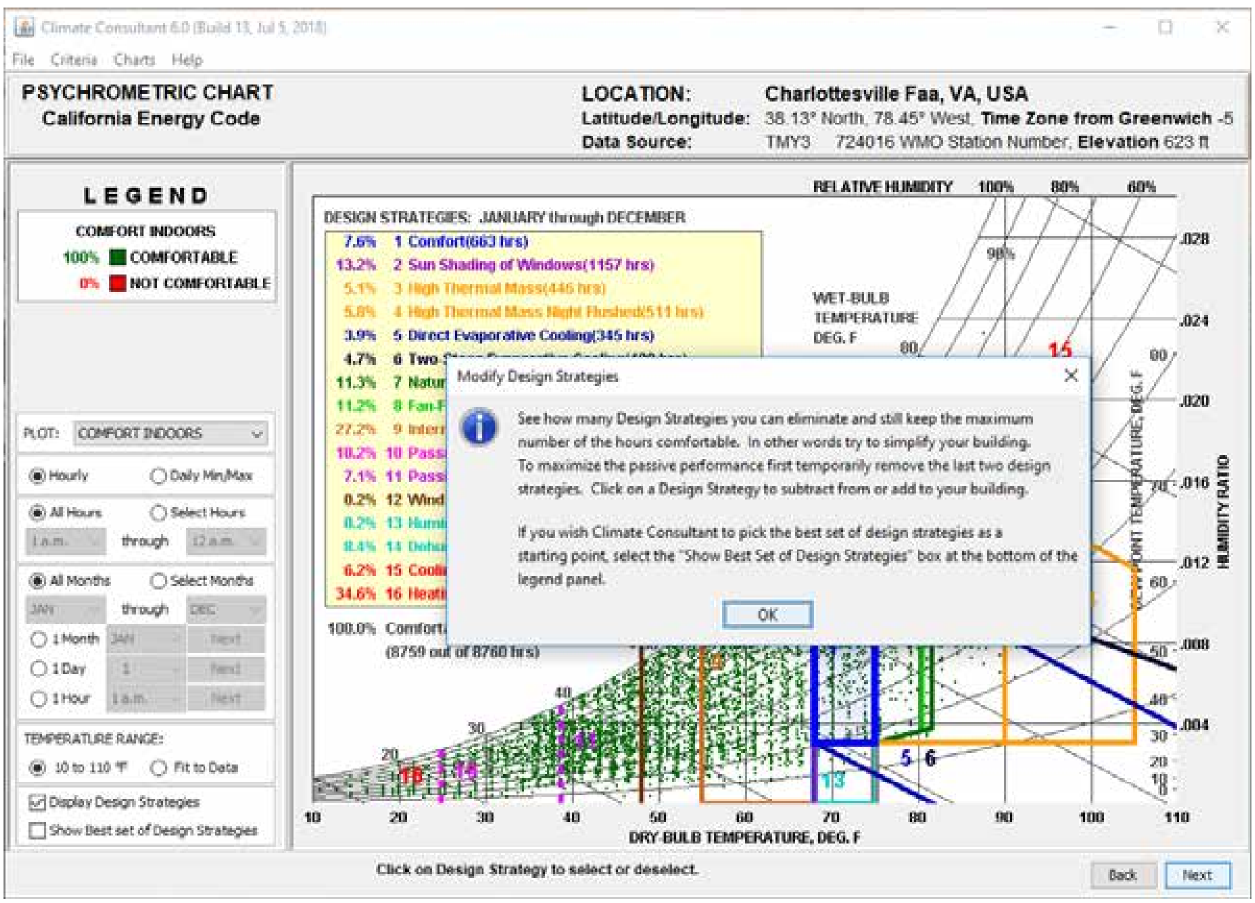


Figure 5-56 Climate Consultant Design Strategies Wizard

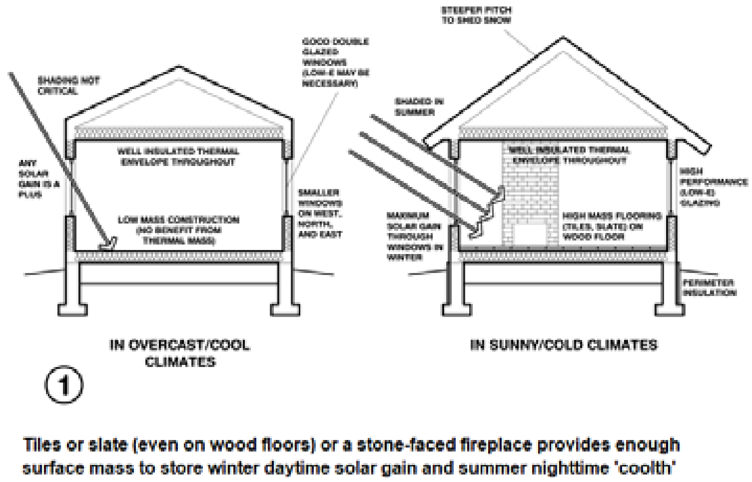
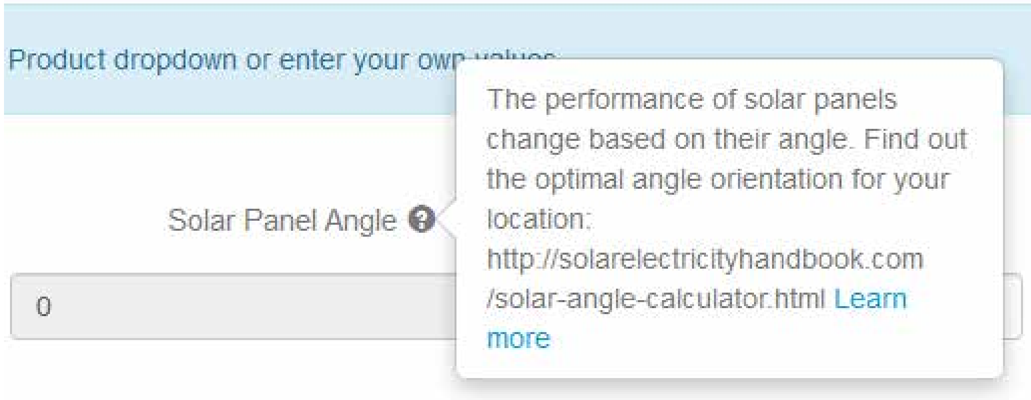


Figure 5-57 Climate Consultant Sample Design Guideline

Similarly, CoveTool provides a direct link to an online solar angle calculator. (Figure 5-58) This suggests that other resources linked by a tool are not limited to reading materials but can include links to other tools as well.



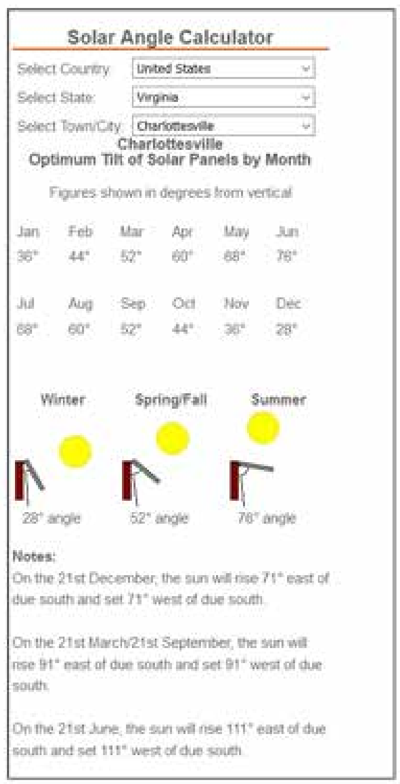


Figure 5-58 Online solar angle calculator link at CoveTool (top) and the calculator itself (bottom)

Other examples of pedagogic tools are certain parts of CoveTool. For instance, in the report section, CoveTool provides an explanation of the results (Figure 5-59) thus helping users with less experience to have a deeper understanding of the results of the analysis.

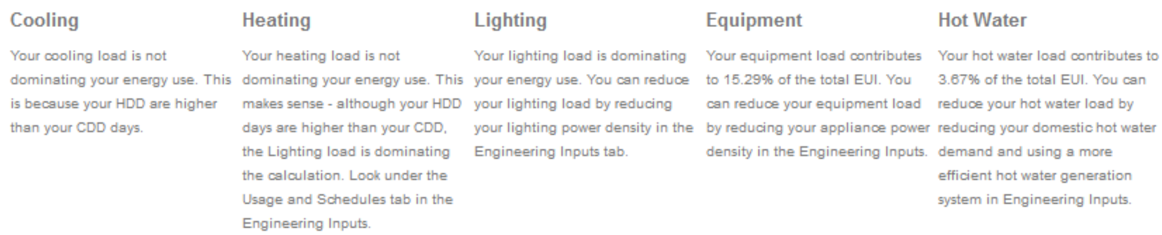


Figure 5-59 Explanation of the results in CoveTool

However, CoveTool is not consistent in this approach. For example, in the results section, CoveTool provides the user with monthly wind-rose diagrams without connecting this information to design strategies such as the orientation of the openings for natural ventilation or shielding from the winter winds. (Figure 5-60) I have noted in my journal that a tool, to be educational, needs to present *processed information* to its user, rather than presenting *raw data*. In other words, the raw data produced as the output of a quantitative analysis should be presented to the user with an overlay of explanatory information. Climate Consultant design guidelines (Figure 5-54) are a good example of such processed information.

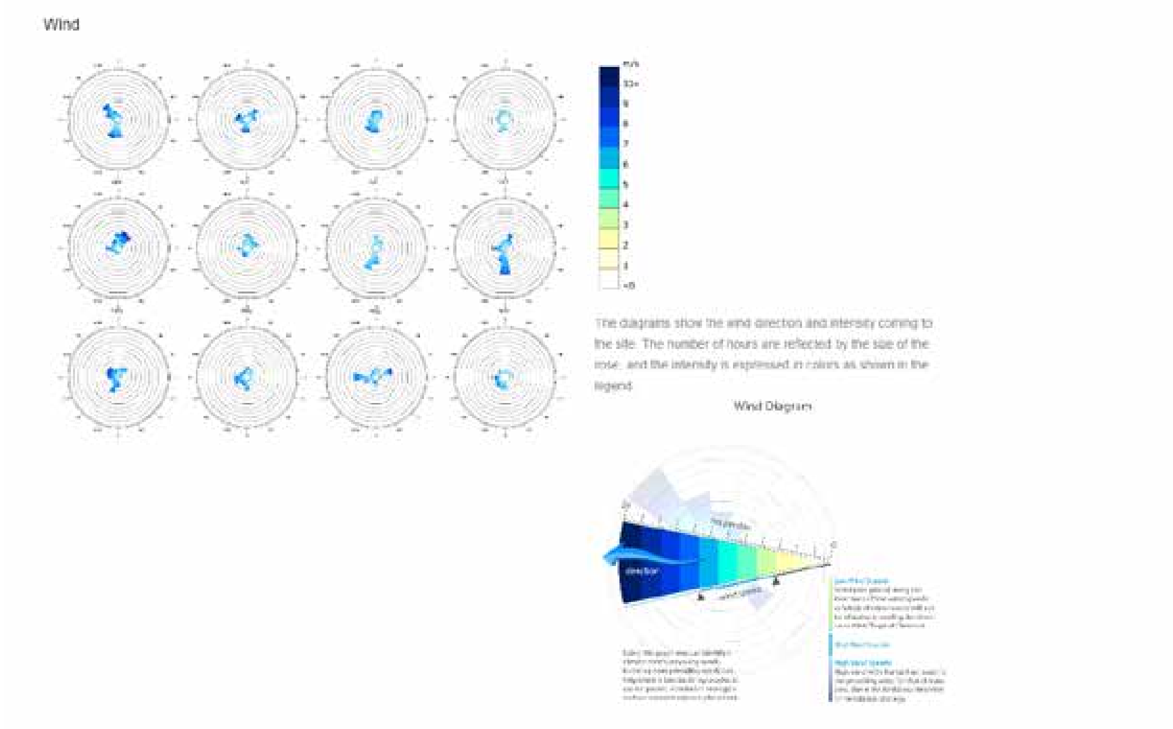


Figure 5-60 Monthly wind-rose diagrams in CoveTool

Both CoveTool and eQuest provide a short explanation for each input field. (Figure 5-61) These explanations make the process of utilizing these tools more educational, however, none of the tools used take advantage of the full potential of this feature. The explanation should contain more information and links to other resources.

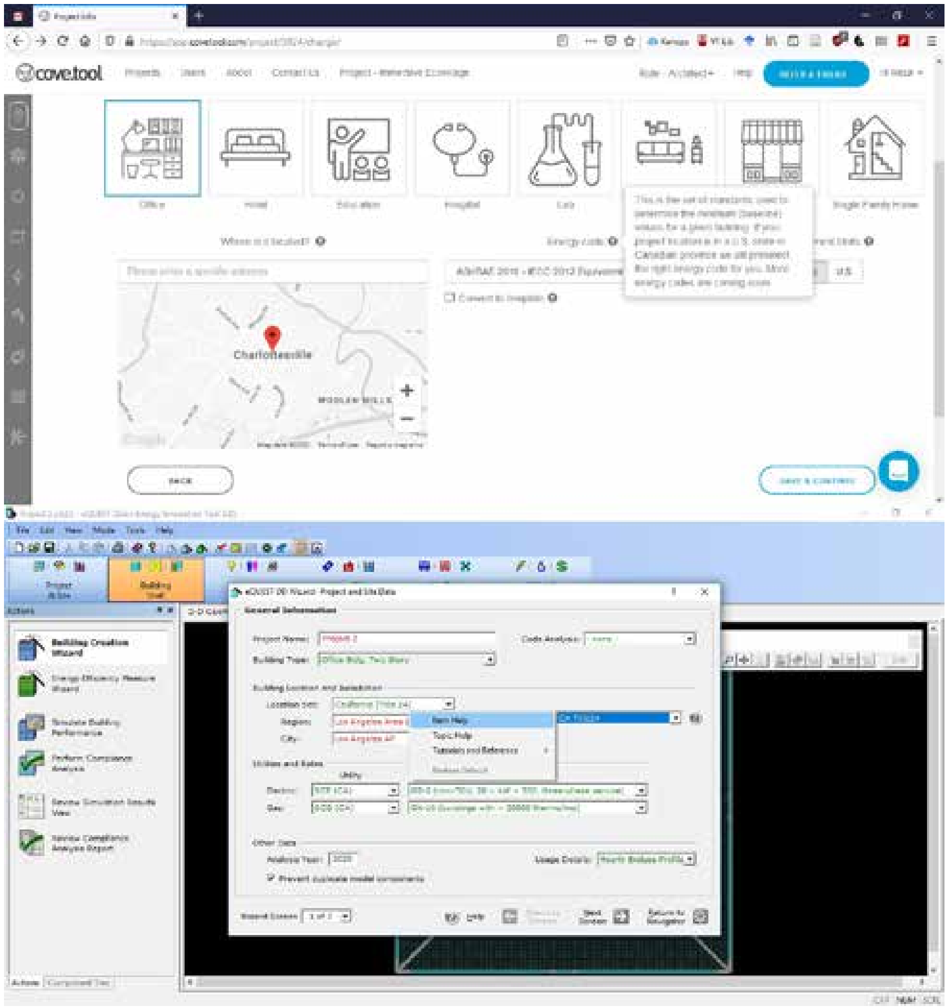


Figure 5-61 CoveTool (top) and eQuest (bottom) input help

5.20.2. Hybrid Environment

As discussed in the previous chapter, the hybrid design environment is intended to question dualities such as digital versus manual tools, and to advocate for an environment that simultaneously employs various manual and digital tools to take full advantage of each approach. For example, while working on the 3D model in SketchUp, I suddenly had an idea to introduce openings (skylights) and PV panels on the roof. I began to develop the idea through a quick sketch in my notebook. However, I realized that if I was able to sketch over the 3D model then I would not need to reproduce the drawing in SketchUp. In an attempt to approach this problem, I took a screenshot of the 3D model and drew a rough sketch over it using the mouse and Photoshop. (Figure 5-62)

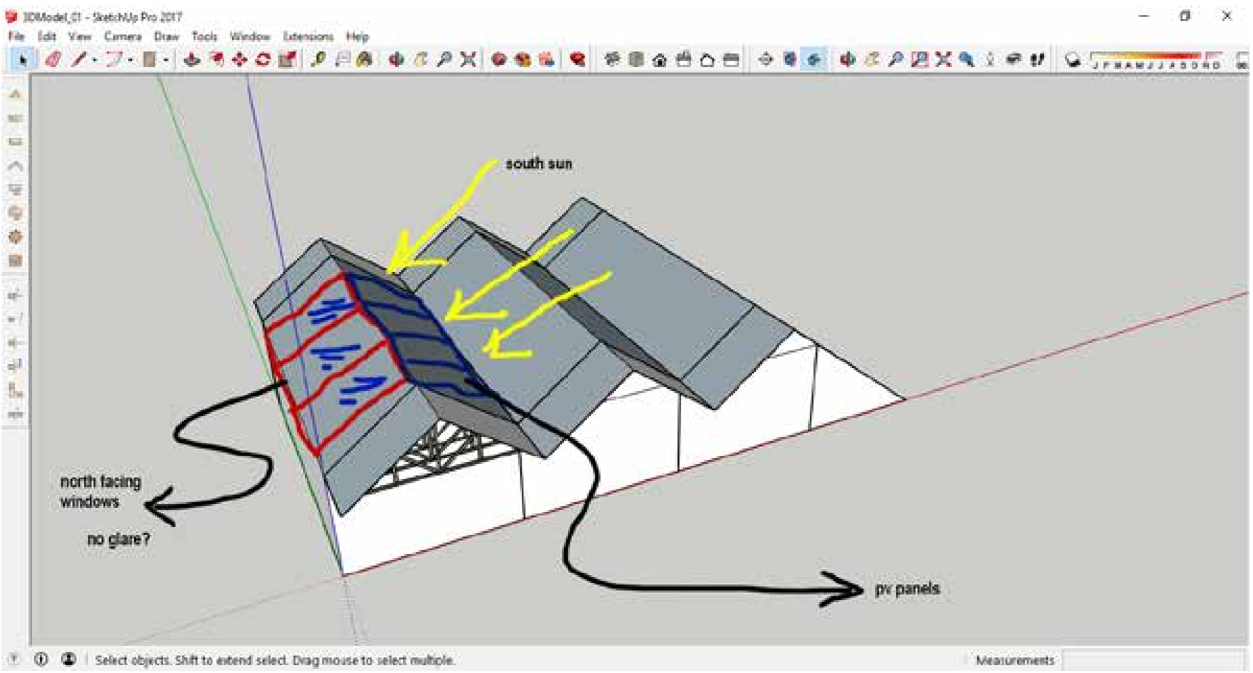


Figure 5-62 Rough sketch over the 3D model using mouse and Photoshop

The mouse was not the proper device for sketching because of the difficulty in drawing a straight line and the lack of a haptic experience. Therefore, I switched to using a Wacom tablet with a stylus. (Figure 5-63) The switch resulted in a much more comfortable process and a more detailed and cleaner sketch. (Figure 5-64)

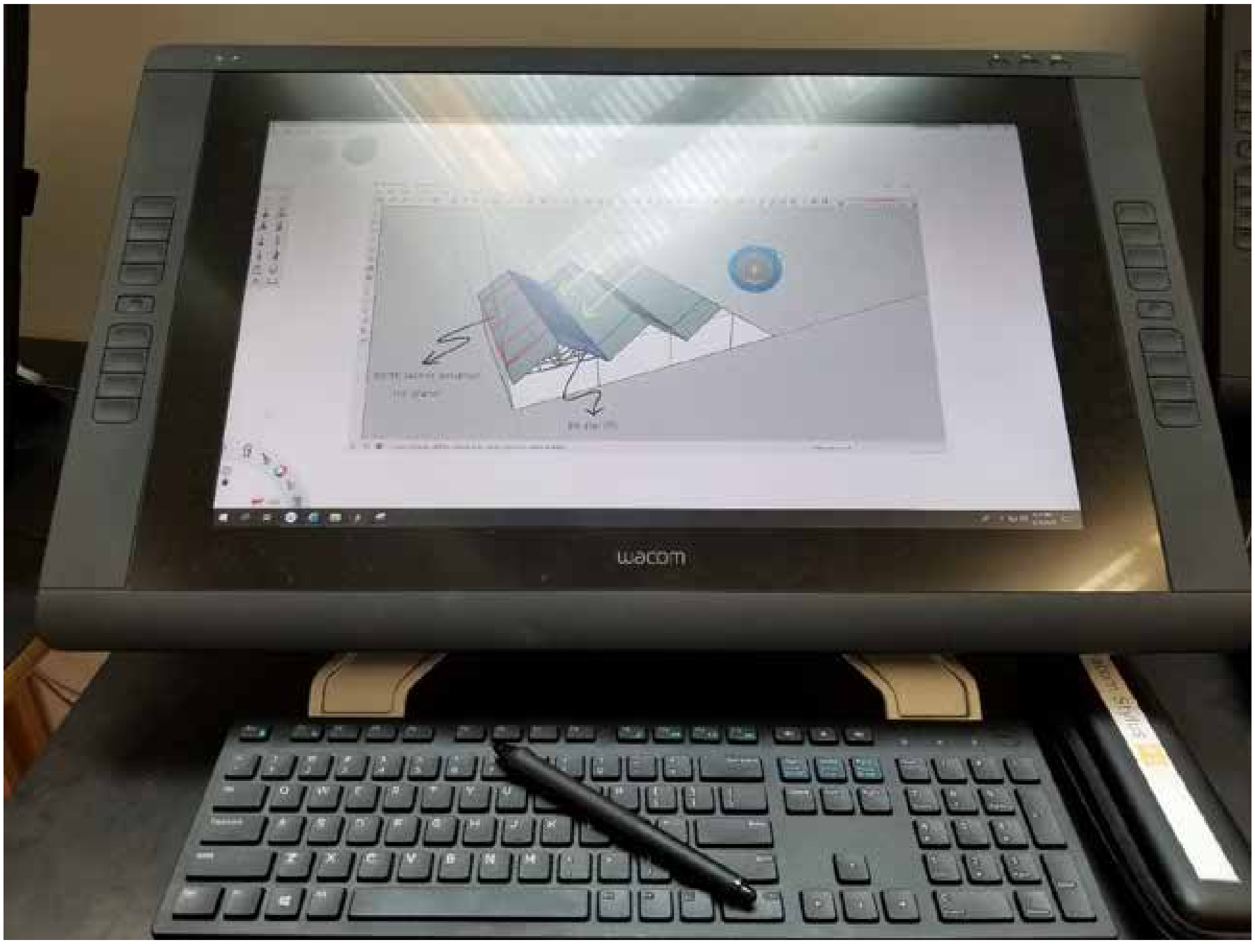


Figure 5-63 Wacom tablet and stylus

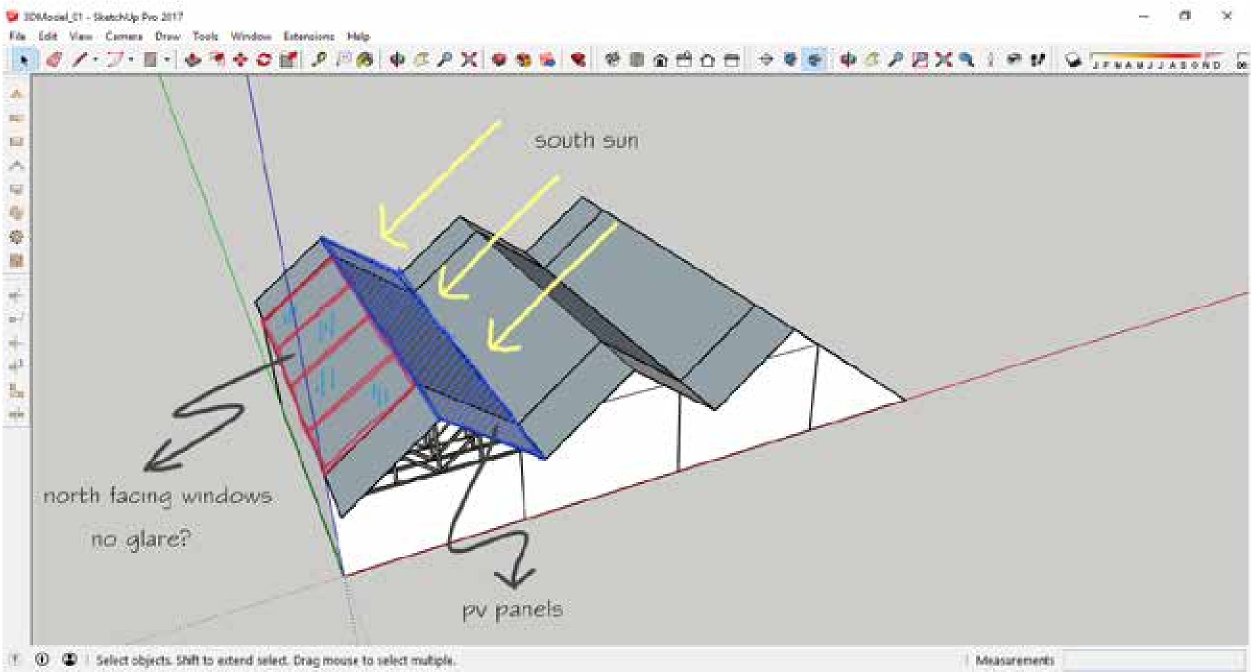


Figure 5-64 Sketch over the 3D model using Wacom tablet and stylus

In Wacom, I used Autodesk SketchBook Pro, although, I noted that while sketching, I only used three features (Figure 5-65):

Pen/brush

Color swatch

Text

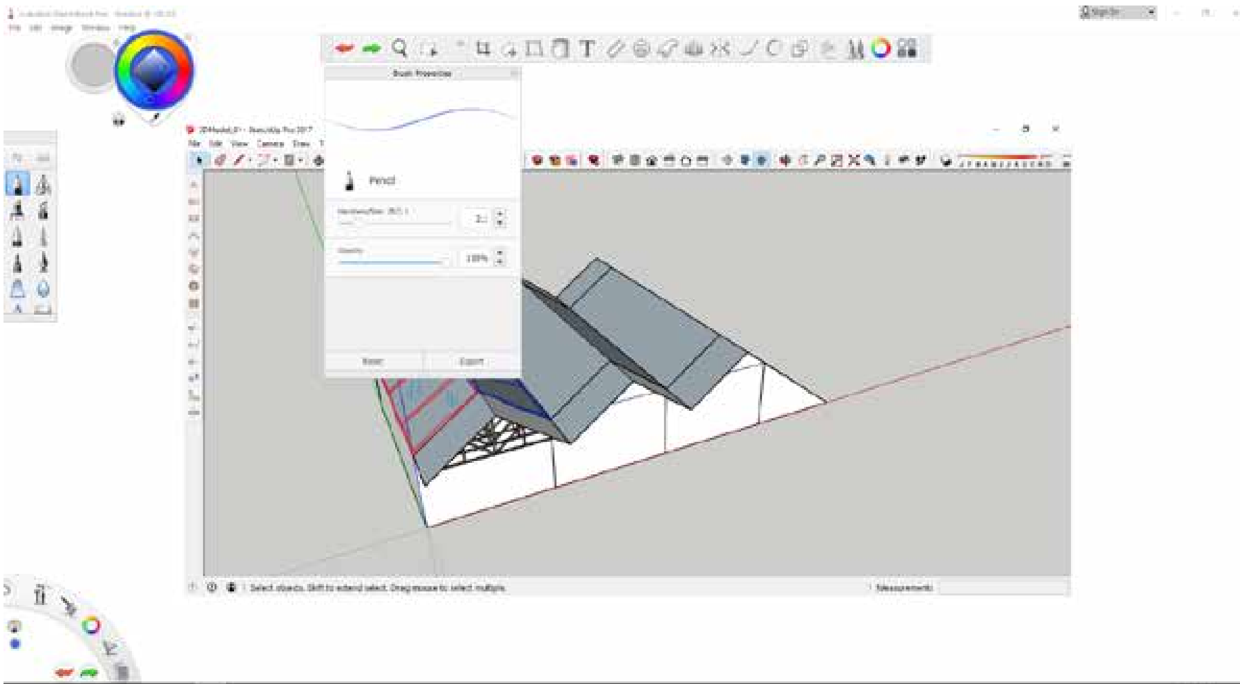


Figure 5-65 Autodesk SketchBook Pro

I have suggested that the availability of features such as this would allow the architect to develop the idea without worrying about how to model that idea in a 3D modeling environment. In a later stage, when the idea has been further developed, the architect can afford to spend more time developing the details in a 3D modeling environment. In other words, this feature can create a thinking space (refer to Thinking Space) within the 3D modeling environment.

Based on this study, I would suggest the following features for sketching inside 3D modeling environments (Figure 5-66):

1. The ability to rotate the drawing surface just like a piece of paper, either physically or inside the software (using the five-finger gesture for instance).
2. The complete horizontal surface is more comfortable for sketching when compared to the slightly tilted surface which is commonly used for drafting.

3. The drawing surface of the tablet needs to be sturdy enough to be able to withstand the user resting his/her hand on it.
4. The glass surface of the Wacom tablet feels unnatural and causes constant slips which lead to frequent mistakes while drawing. A surface with more friction, more similar to paper (for instance similar to e-ink surfaces), would reduce this problem.
5. An application that behaves like a piece of caulk paper. The architect can open it over any other application and start sketching, using the drawing on the other application as a layout. The caulk paper application would automatically save a screenshot of whatever is behind it as well in a layer that can be turned on and off.

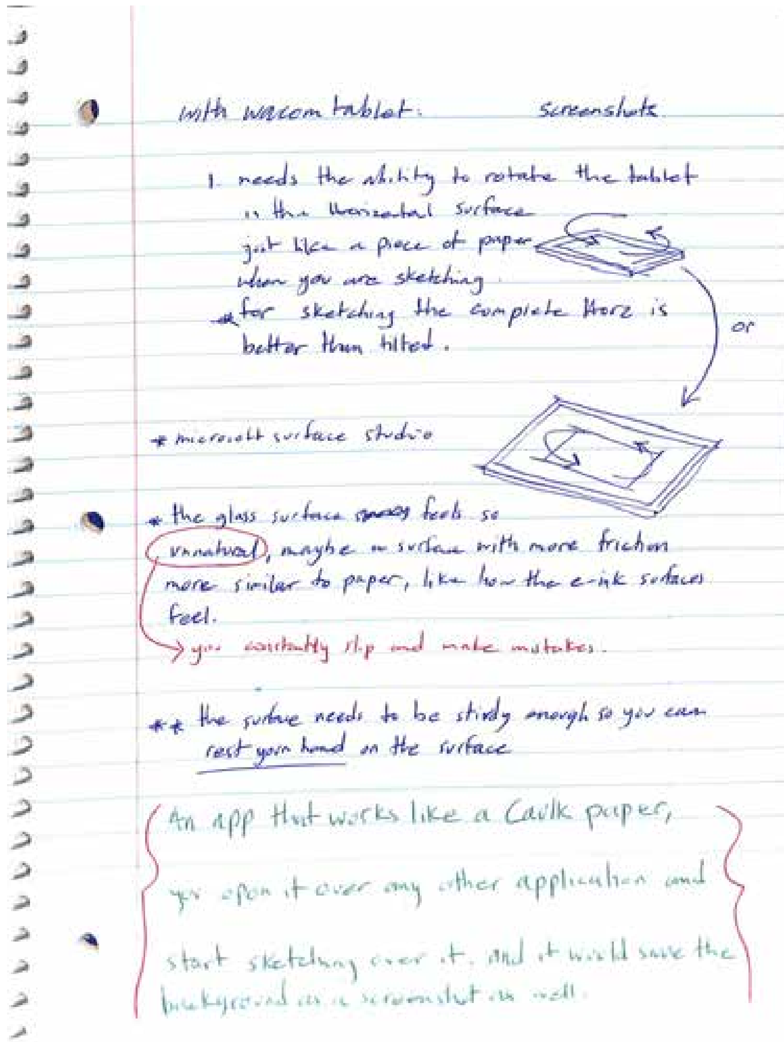


Figure 5-66 Journal page suggesting features for Sketching on a tablet

These features extend those discussed by Al-Rqaibat (2019) on her research about possibilities for hand sketching in digital design environments by incorporating the haptic responses and advocating for a hand sketching environment that can work as part of other design environments, creating a hybrid design environment.

A similar exploration was with hand sketching in the AutoCAD environment. While trying to develop the plan, I have noted that the AutoCAD drafting environment can be useful in the early stages of the design process. In this environment, the drawings can be properly scaled, and the rooms designed with dimensions that support the intended activities while reducing the need for significant re-dimensioning during design development. However, AutoCAD is too rigid to support ideation in the very early stages. It does not have tools that support the creation of schematic drawings and modification of drawings are time-consuming (fast iterations are a requirement for design studies at the early stages of the design process).

For this reason, I have suggested that AutoCAD be modified to include a sketch overlay feature that would support the development of the initial layout. Then the architect can utilize the AutoCAD drafting features to correct the scaling and add details. With this in mind, I tried to create a mockup version of this feature by taking a screenshot of the AutoCAD drawing and transferring this to Photoshop where I used the Microsoft Surface Studio computer and stylus (Figure 5-67), to draw a schematic layout of the plan. (Figure 5-68)

Figure 5-67 Microsoft Surface Studio computer and stylus

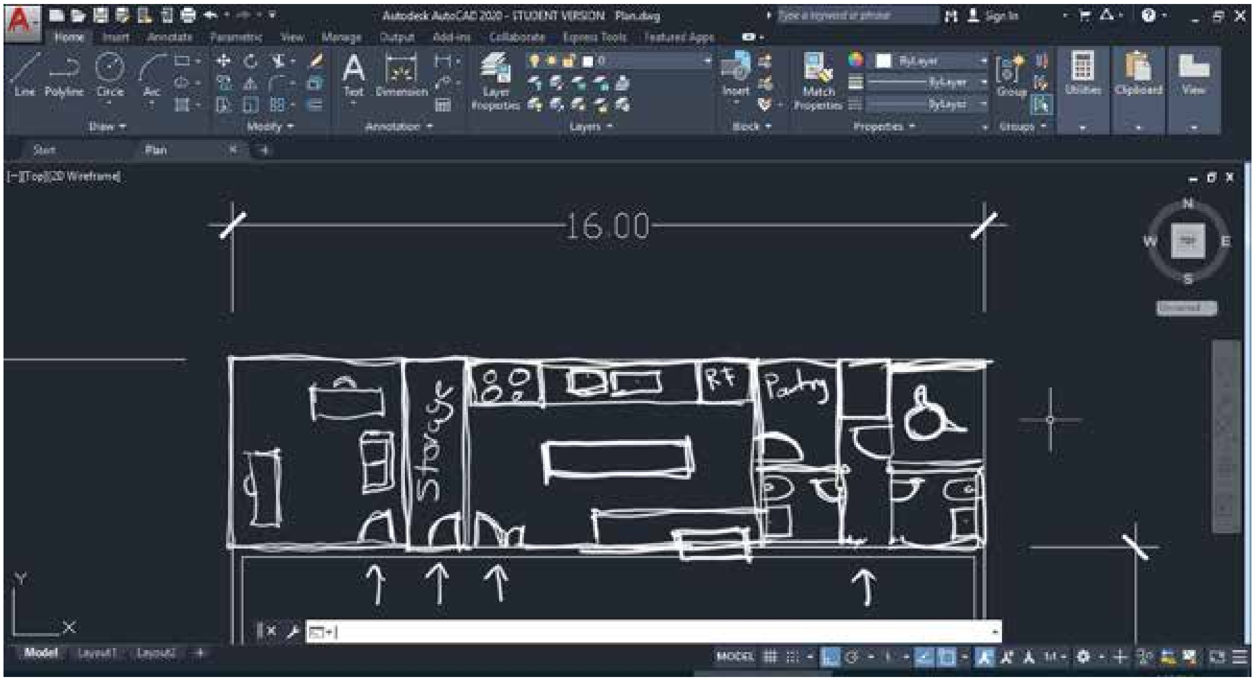


Figure 5-68 Hand-sketched schematic layout of the plan in AutoCAD

Later, I imported the hand-sketched plan to AutoCAD, reduced the brightness, and drafted a scaled plan drawing over the layout. (Figure 5-69) I have noted that I felt that this "was much better, it felt that I have an idea and I'm working on that, instead of just moving and rotating rectangles (spaces) and hope for a layout." (2020)

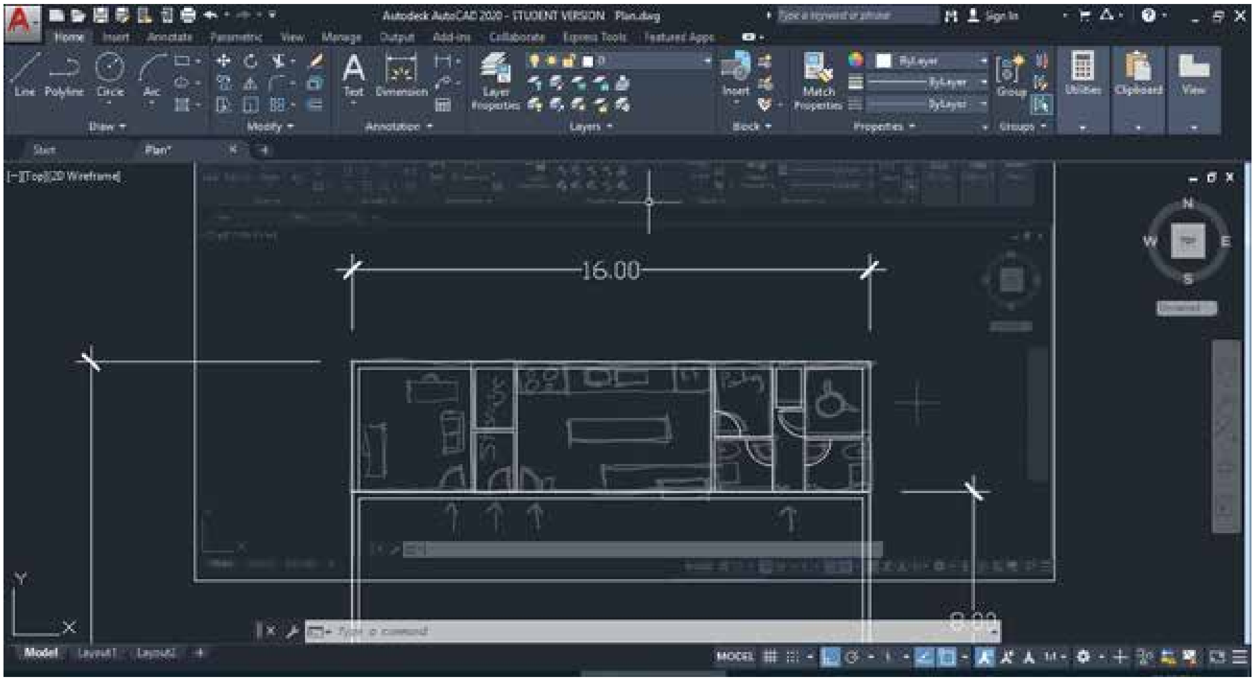


Figure 5-69 Drafting the plan over the schematic layout plan

An existing example of the type of hybrid environment that I am proposing is the default views in Rhino. (Figure 5-70) The top, front, right, and perspective views that are visible by default in Rhino enable the user to quickly switch from 3D to a 2D drafting environment, which is more appropriate for tasks such as trimming or drawing the outline of a shape. However, these views are appropriate for drafting and have not been developed to support ideation at the early stages of the design process. Including hand sketching capabilities, such as those discussed for AutoCAD, can help to address this limitation.

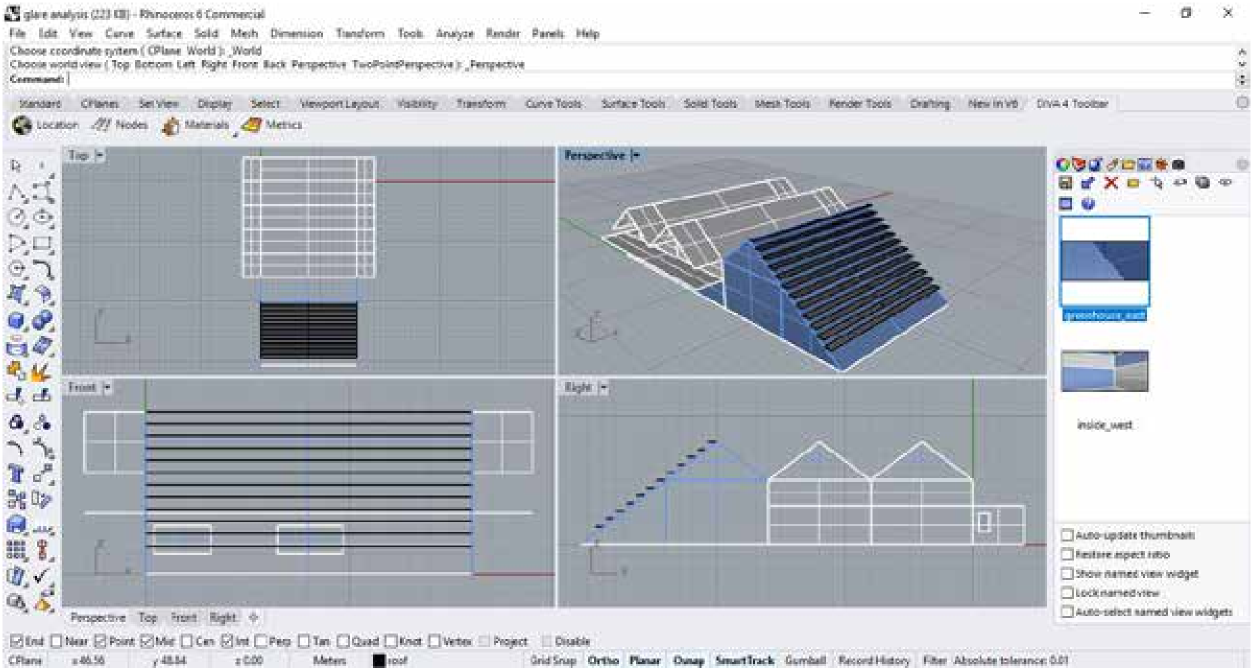


Figure 5-70 Default views in Rhino

5.21. Feature - All Stages Themes

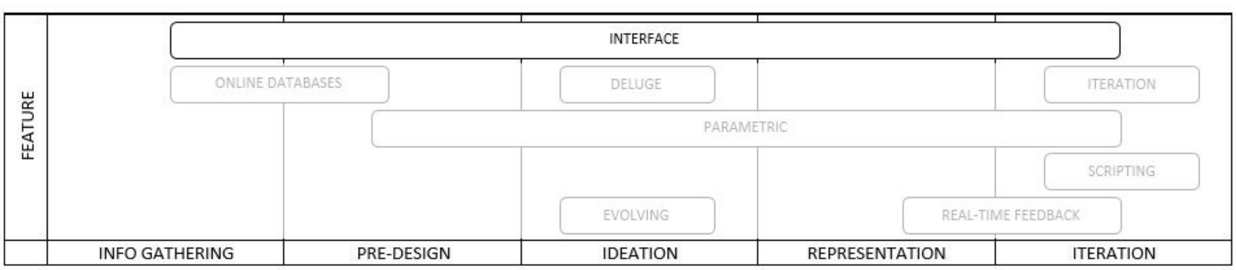


Figure 5-71 Feature - All Stages Themes

5.21.1. Interface

I have noted in my journal that the wizard interface (a sequence of screens with input prompts that build on previous inputs), in tools such as Climate Consultant and eQuest, is very appropriate for the relatively simple and very sequential process (Figure 5-72) that these tools follow.

Figure 5-72 Wizard Interface Logic

Related to the *Fuzzy vs. Precise* and the *Timing* themes, the complexity of the interface can be an important criterion when choosing between different tools, depending on the current level of the design development. I have documented my thought process while deciding which 3D modeling software to choose when moving from hand sketches to a digital 3D model. Between Revit, Rhino, and SketchUp, I chose SketchUp. I have argued that the SketchUp interface "feels more minimalistic and fluid" (2020) which is necessary during the early phase when "I need to still play with my form." (2020)

5.22. Summary

Table 5-1 provides a timeline of the design tasks that were performed during the immersive case study step. For each task, it provides the objectives as well as the tools which were used to achieve them for both qualitative and quantitative aspects of that task. Also, the table connects this information to the framework by providing the themes that were addressed by each task and suggesting strategies for qualitative and quantitative synthesis.

Table 5-1 The immersive case study timeline and the qualitative and quantitative synthesis strategies

Design Task	Qualitative		Quantitative		Framework Themes	Qualitative and Quantitative Synthesis
	Objectives	Tools	Objectives	Tools		
Info gathering / Program development	Spaces / Spatial relations and qualities	Time-Saver Standards / Google Images / ArchDaily	Areas / Code requirements	Time-Saver Standards / Building code websites	*A priori* knowledge / Online databases / Architecture community involvement	

Design Task	Qualitative		Quantitative		Framework Themes	Qualitative and Quantitative Synthesis
	Objectives	Tools	Objectives	Tools		
Pre-design / Context	Site study	Google Earth	Climate study	Climate Consultant	Frameworks / Online databases / Timing / Pedagogic tool	Overlaying qualitative and quantitative information
Pre-design / Inspiration	Formal inspiration	ArchDaily	Design guidelines and strategies	2030 Palette / Climate Consultant	Frameworks / Timing / Pedagogic tool	
Ideation / Presentation	Concept/Form generation	Hand sketching	Incorporation of design guidelines and strategies	Hand sketching	Fuzzy vs. Precise / Multiple levels of abstraction	
Design Development / Roof pitch angle			PV panel incorporation possibility	Diva	Scripting / Pedagogic tool	
Design Development / Energy model			Orientation and Window to Wall Ratio (WWR)	eQuest / CoveTool	Evolving / Interface / Understanding and Validating Output / Timing / Architect's control / Real-time feedback / Audience / Pedagogic tool	Energy, daylight and view real-time feedback / Various roles working on the model and using 3D comments for communication
Design Development / Plan Development	Developing the spatial relations	Hand Sketching / Drawing tablet / Photoshop	Developing a scaled plan	AutoCAD	Hybrid environment	Hand sketching in the AutoCAD environment
Design Development / 3D model development	Studying the spatial characteristics / Developing details	SketchUp / Medeek Truss and Oob Terrain plugins	Developing a 3D model for advanced energy and daylighting analysis	SketchUp / Rhino	Thinking space / Architect as Toolmaker / Fuzzy vs. Precise / Real-time feedback / Pedagogic tool / Hybrid environment / Interface	Using VR for interior investigations

Design Task	Qualitative		Quantitative		Framework Themes	Qualitative and Quantitative Synthesis
	Objectives	Tools	Objectives	Tools		
Design Development / Glare analysis			Studying glare conditions / Designing shading for the greenhouse	Diva	Pedagogic tool	Using VR for glare and view real-time feedback
Design Development / Physical model development	Studying spatial characteristics / Developing details /Studying Materials	Physical modeling			Multi-sensorial / Deluge / Thinking space / Manual vs. Digital differences	
Design Development / 3D model development - Interior	Studying spatial characteristics / Developing details /Studying Materials	Modelo / Google Cardboard			Dialogue / Real-time feedback	

The immersive case study step provided the opportunity to vastly expand and deepen my understanding of the themes and their relations that emerged during the literature review and the interviews. One new theme was emerged during the case study, the open standard format. (Figure 5-73) However, some modifications and new thematic relations were added to the framework. (Please refer to Figure 4-25 for an overview of the framework before the immersive case study step.)

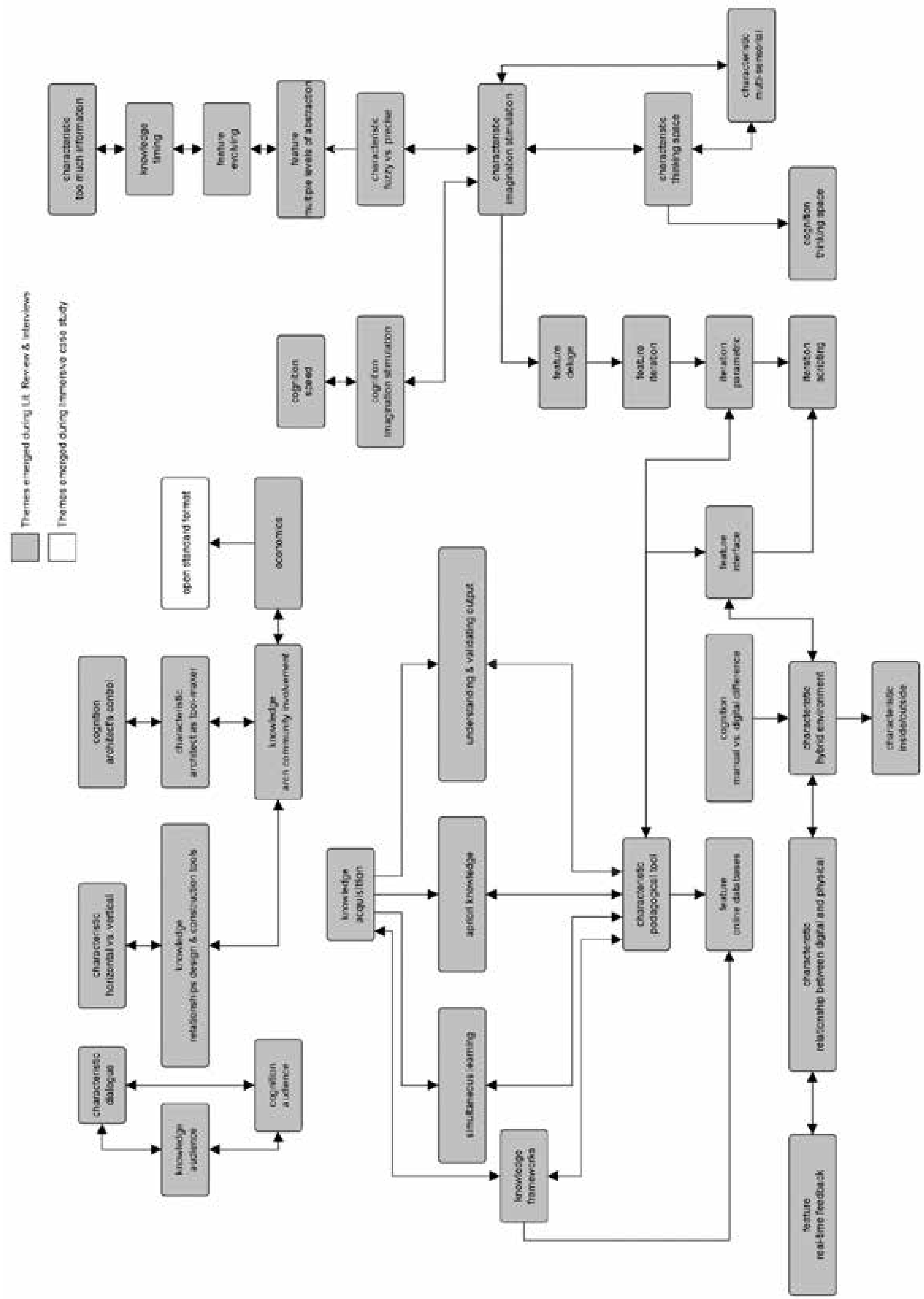


Figure 5-73 Themes emerged during the literature review and the interviews versus those that emerged during the Immersive Case Study

Figure 5-74 provides an overview of the tools that I used during the immersive case study and a summary of their supportive features as well as the suggested modifications. A more in-depth discussion of these features and suggested modifications were presented in this chapter.

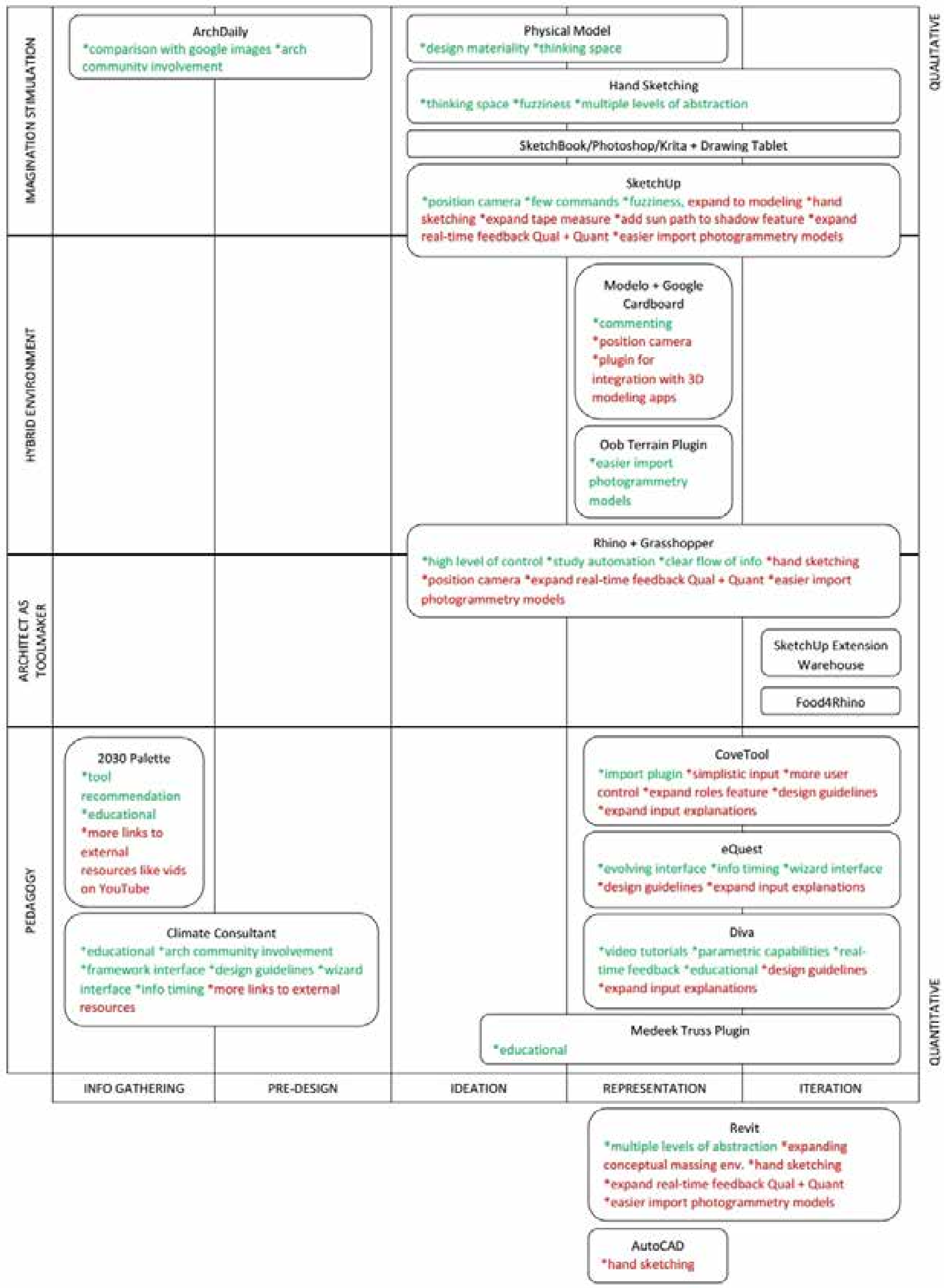


Figure 5-74 Summary of immersive case study addressed issues and suggested modifications

6. Delphi Method

6.1. Introduction

As described in chapter three (methodology), the Delphi method was used to finalize the framework and establish the credibility of the findings. The Delphi included a panel of experts consisting of seven individuals: five were university faculty members from various architecture schools with research and teaching interests related to daylighting, application of digital tools in the design process, and the boundary between qualitative and quantitative assessments; and two were architects active in professional practice with previous experience working on projects which had a strong emphasis on both qualitative and quantitative studies throughout the design process. (Table 6-1)

Table 6-1 Participants' Background Information

Participant	Profession	Expertise
#1	architecture professor	He is a professor at a school of architecture since 2005. He has extensively taught courses and published on the topics of Computational Methods in Design, Building Information Modeling, Visualization, and Augmented Reality. His research projects have been funded by the National Science Foundation (NSF), the U.S. Department of Energy (DOE), National Endowment for the Humanities (NEH), and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE).
#2	architect	He works for an internationally active architecture firm based in Canada. He has been involved in several architectural design projects both in the United States and Canada including an entry to the US DOE Solar Decathlon competition. His master's thesis includes a case study of light.
#3	architecture professor	He is an assistant professor at a school of architecture since 2014. His research area includes energy modeling and computational fluid dynamics (CFD).

Participant	Profession	Expertise
#4	architecture professor	She is an assistant professor at a school of architecture since 2019. Before her current position, she was a practicing architect working on projects in Europe, United States, and Asia. Her research explores interactions between science and architectural design.
#5	architecture professor	He is a faculty at a school of architecture since 2017. His PhD research has been about sustainability and architecture education.
#6	architecture professor	He is an assistant professor at a school of architecture since 2008. His PhD research has been about the incorporation of quantitative ventilation considerations into the design process.
#7	architect	He has been involved in several architectural design projects including a winner entry to the Solar Decathlon competition. His master's thesis investigated possibilities for circadian lighting design in architectural spaces.

An %80 threshold was deemed appropriate to achieve consensus on the applicability of the research outcomes and end the Delphi process. Diamond et al. compared 100 studies that used the Delphi method, with 98 percent of the studies having consensus as an aim. (2014, p. 401) They reported that *percent agreement* was the most common definition for consensus and the median threshold for determination of consensus was 75%. (2014, p. 404)

6.2. The Delphi Panel Process

The Delphi study consisted of two rounds of interactions. In the first round, an online presentation was shared with the participants through a website created by the researcher. The online presentation provided a description of the research questions, the methodology used, and a summary of the findings (the framework). A detailed explanation of this presentation is provided in The Initial Presentation section below. At the end of the online presentation, the participants were asked to answer two questions using an online commenting section (Figure 6-1):

1. Do you think this framework addresses all aspects of the problem? If not, what aspects are missing?
2. Do you agree with the categorization of the themes under this framework? If not, what changes would you suggest?

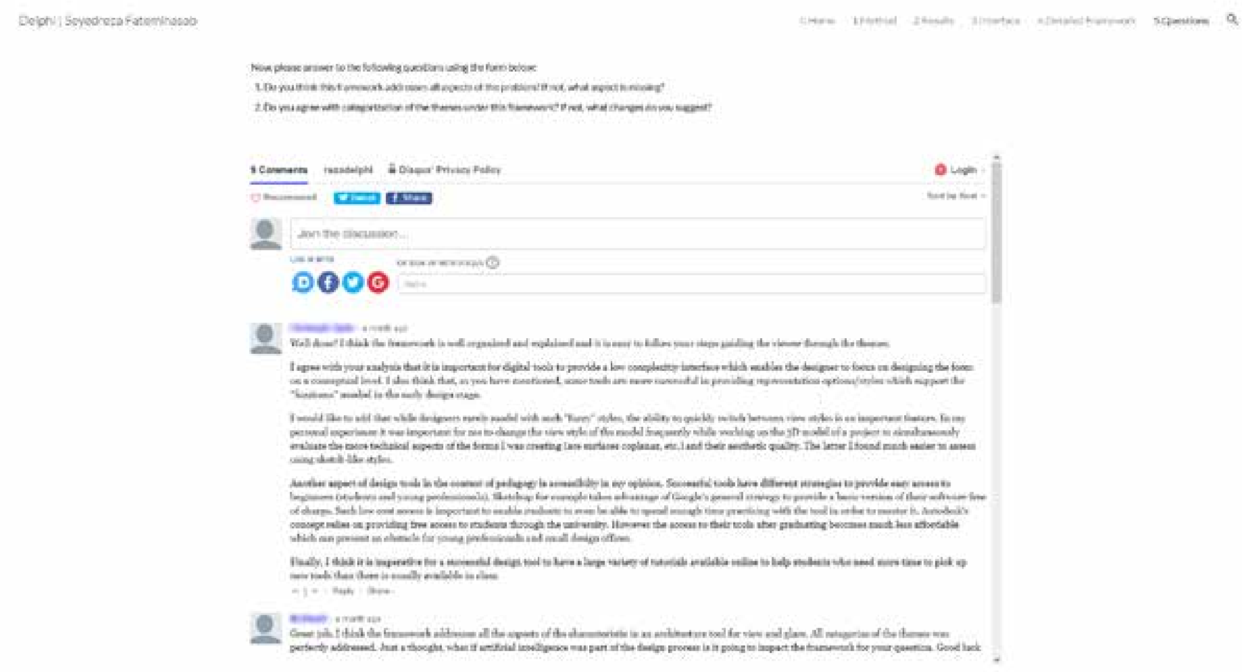


Figure 6-1 A screenshot from the online commenting section

The responses were analyzed after all participants replied to these two questions. At the end of the first round, 2 out of the 7 participants (29%) indicated that they believe the framework addresses all aspects of the problem and they agreed with the categorization of the themes and therefore provided no suggestions for expansion. Since the consensus threshold was not achieved by the first round of the Delphi panel, a report consisting of the comments provided by the participants was produced and sent to each participant for the second round of the Delphi panel. For a summary of this report and the suggestions by the participants refer to The Report section, later in this chapter.

In response to this report and the application of their recommendations in the first round, all seven participants (100%) answered yes to the question of whether they believe that the framework is complete and applicable. Since the consensus threshold was achieved in this round, the Delphi study was concluded.

6.3. The Initial Presentation

This section describes the initial presentation as it was presented to the participants during the first round of the Delphi study. The participants viewed this information on several sequential webpages. It also included a series of videos demonstrating the major concepts and themes that emerged from the research. Since it is not possible to include those videos in this document, they have been replaced with screenshots from them.

After a short description of the research questions and methods, the framework was presented to the participants in several pages. The first page suggested that four major themes need consideration while developing architectural tools to support simultaneously addressing qualitative and quantitative criteria during the early stages of the design process (Figure 6-2):

1. For quantitative studies, such as glare analysis, a more robust knowledge acquisition strategy is needed.
2. For qualitative studies, such as view study, the tools' role as a stimulus of imagination should be emphasized.
3. For bridging the gap between qualitative and quantitative studies, the design environment (the constellation of the tools and methods used by the architect) should be a hybrid environment, one that includes both manual and digital tools, immersive and non-immersive digital representations, etc.
4. For bridging the gap between qualitative and quantitative studies, the role of the architect as toolmaker and design environment coordinator should be emphasized. It does not mean that the architect should be the developer of the tools but rather the architect should be the person who connects various tools and thus creates a

unique constellation that helps to define the design problem from a certain perspective.

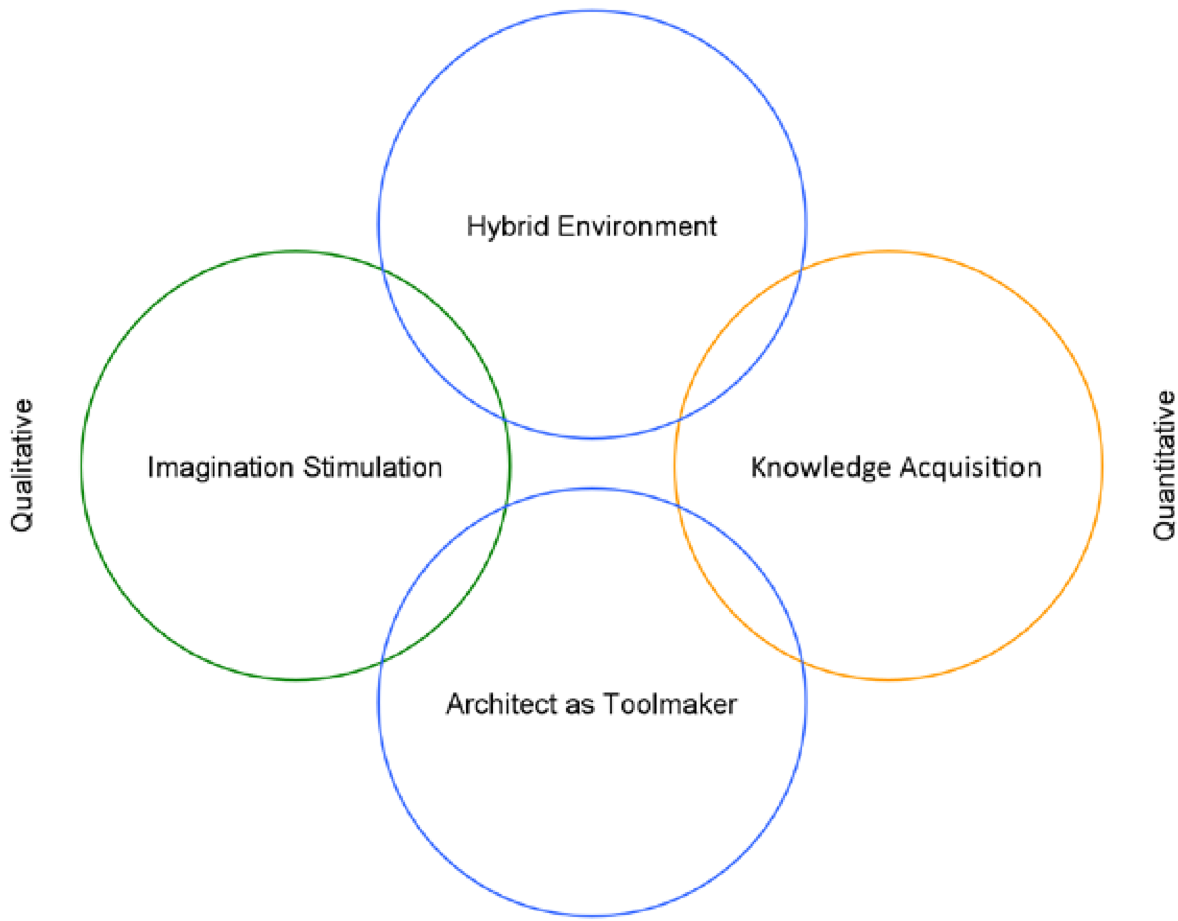


Figure 6-2 The four major themes for simultaneously addressing qualitative and quantitative criteria

The second page pointed out that the central feature that connects all these themes is the interface of the tool (Figure 6-3) and its ability to support two processes:

1. The iteration stage during the design process
2. The ability of the interface to evolve and correspond to the demands and characteristics of different stages of the design. (Figure 6-4)

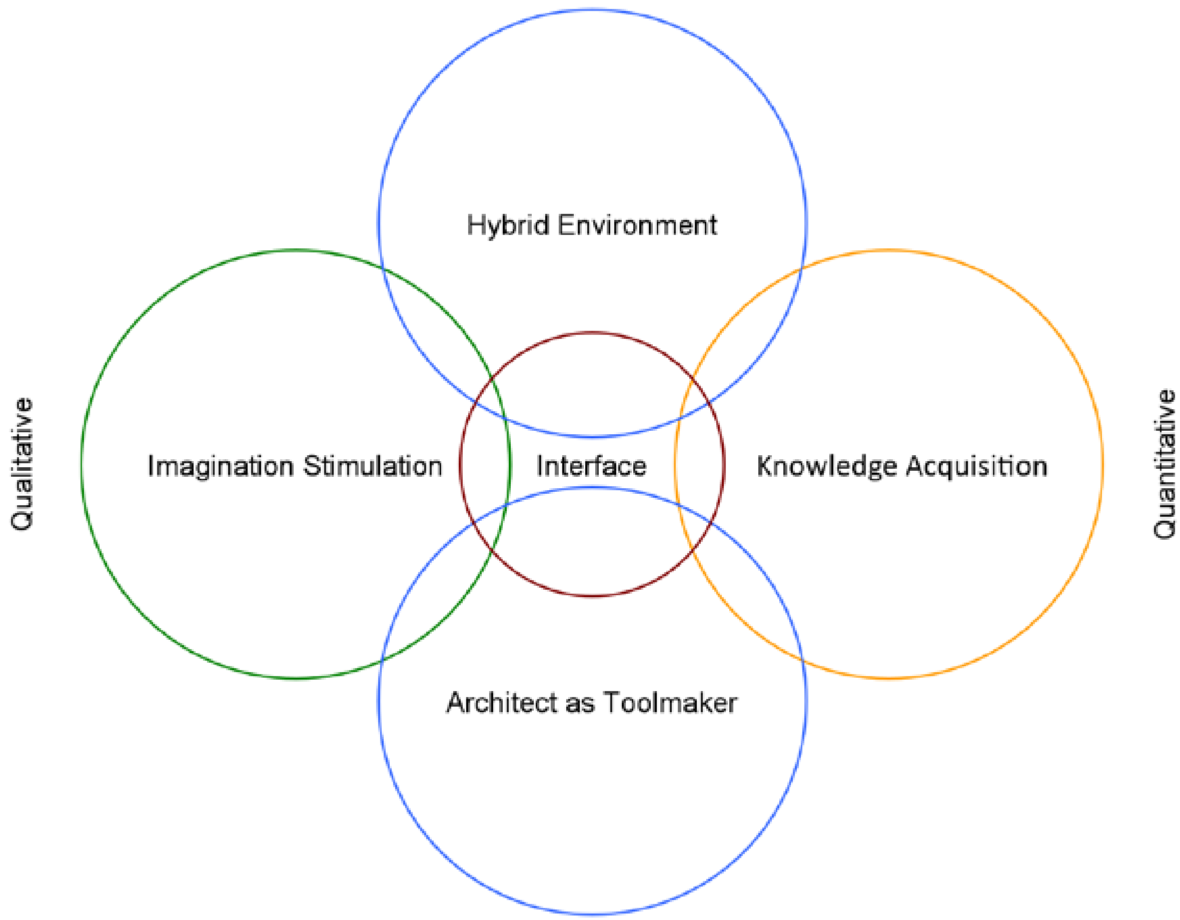


Figure 6-3 The central role of the Interface theme

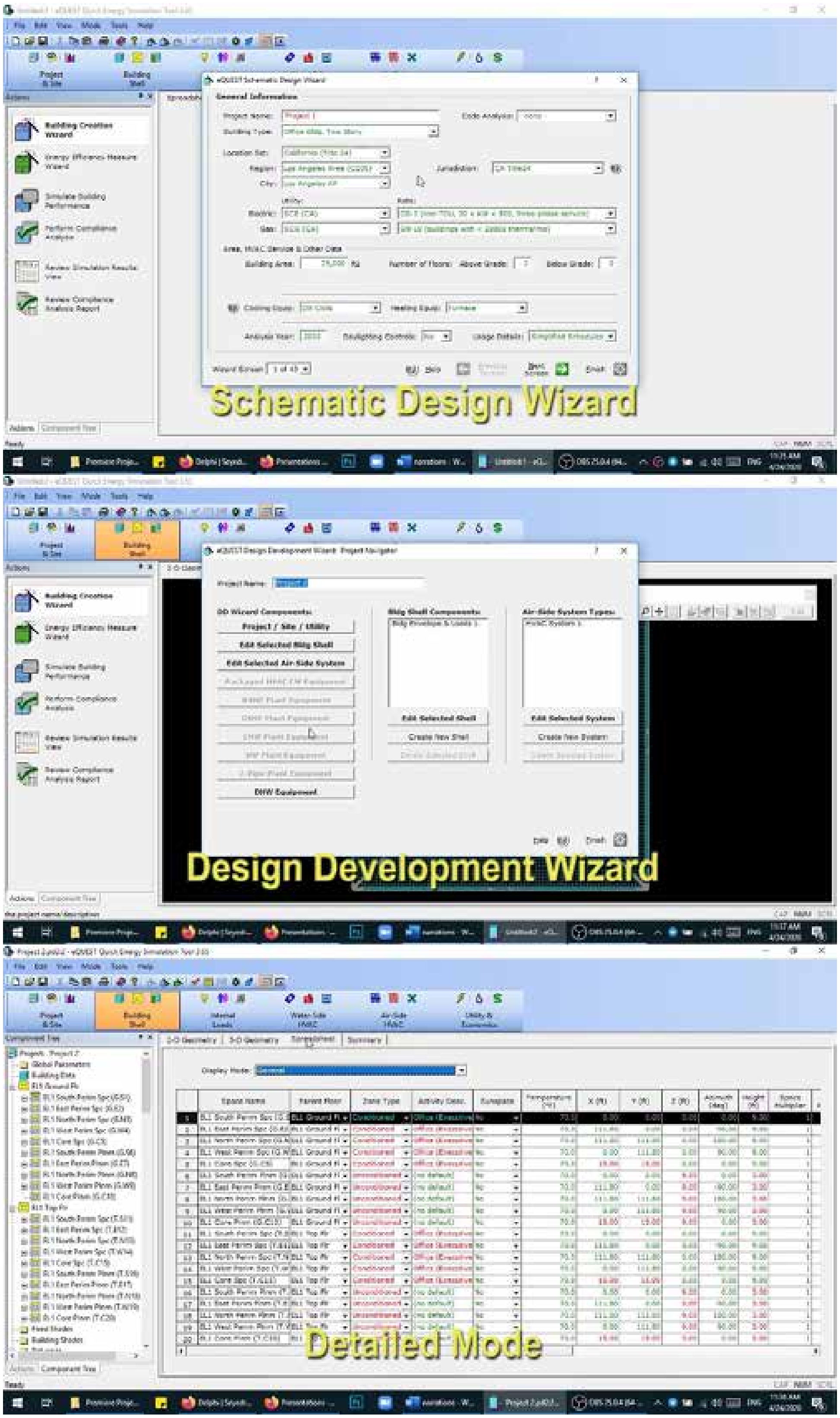


Figure 6-4 Screenshots from the video demonstrating the evolving interface of eQuest

On the next page, a detailed version of the framework was presented using a diagram (Figure 6-5). It also provided the participants with the option to click on any of the four major themes to get a more detailed explanation of them. The following sections present these detailed explanations.

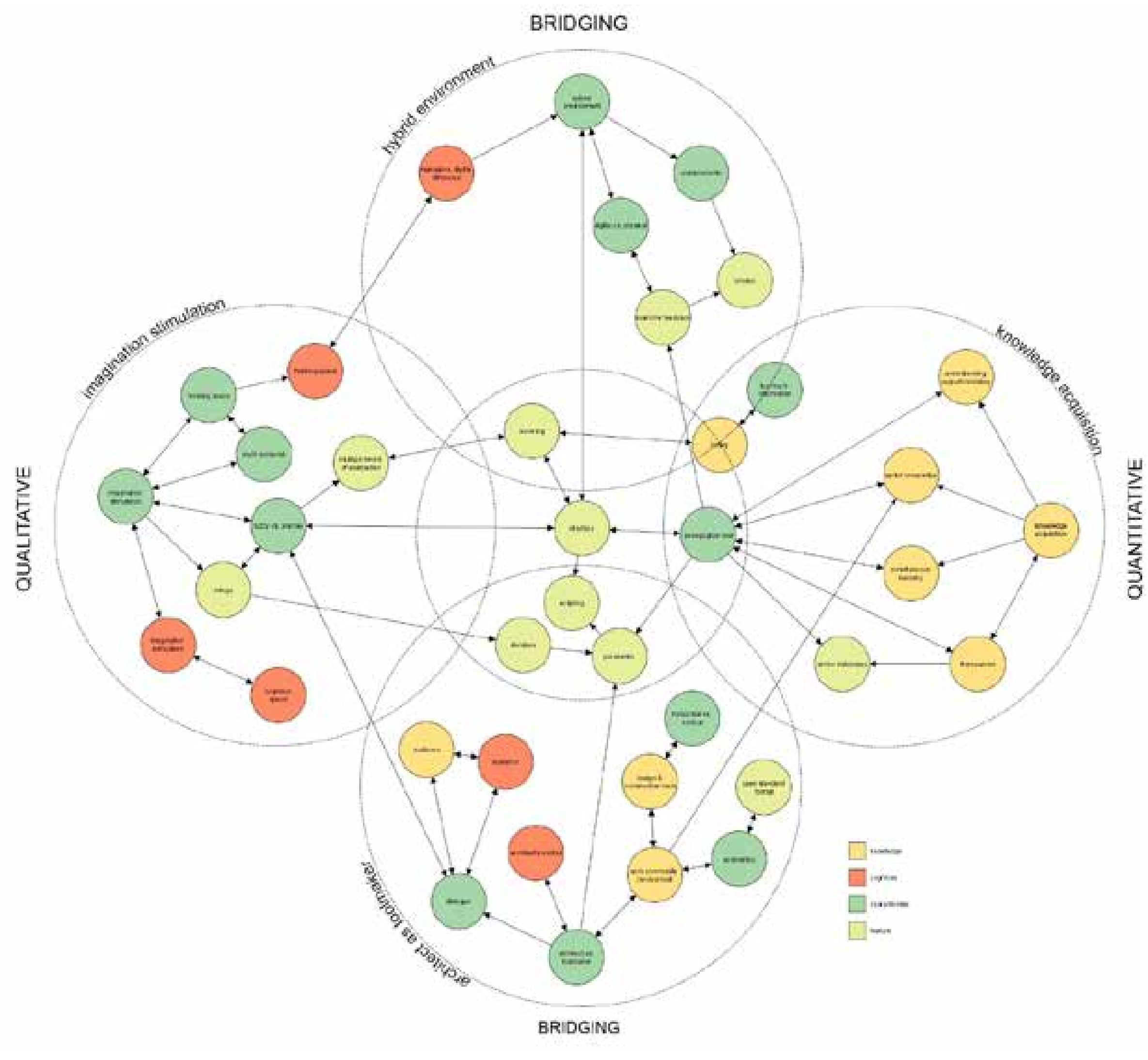


Figure 6-5 The detailed framework

6.3.1. Imagination Stimulation

This page provided a list of *Imagination Stimulation* sub-themes (Figure 6-7) which discuss:

- Thinking Space: the ability of the design environment to create a space that supports design thinking
- Multi-sensorial: the ability of the design environment to simultaneously stimulate various senses
- Fuzzy vs. Precise: a correct balance between fuzziness and preciseness of the representations based on the design stage (Figure 6-6)
    - Multiple levels of abstraction: the ability of the design environment to simultaneously address multiple levels of abstraction from general concepts to small details
- Deluge: the ability of the design environment to support the production of unintentional information that can help to stimulate the imagination
- Speed: attention to speed limits inherent in design cognitive processes

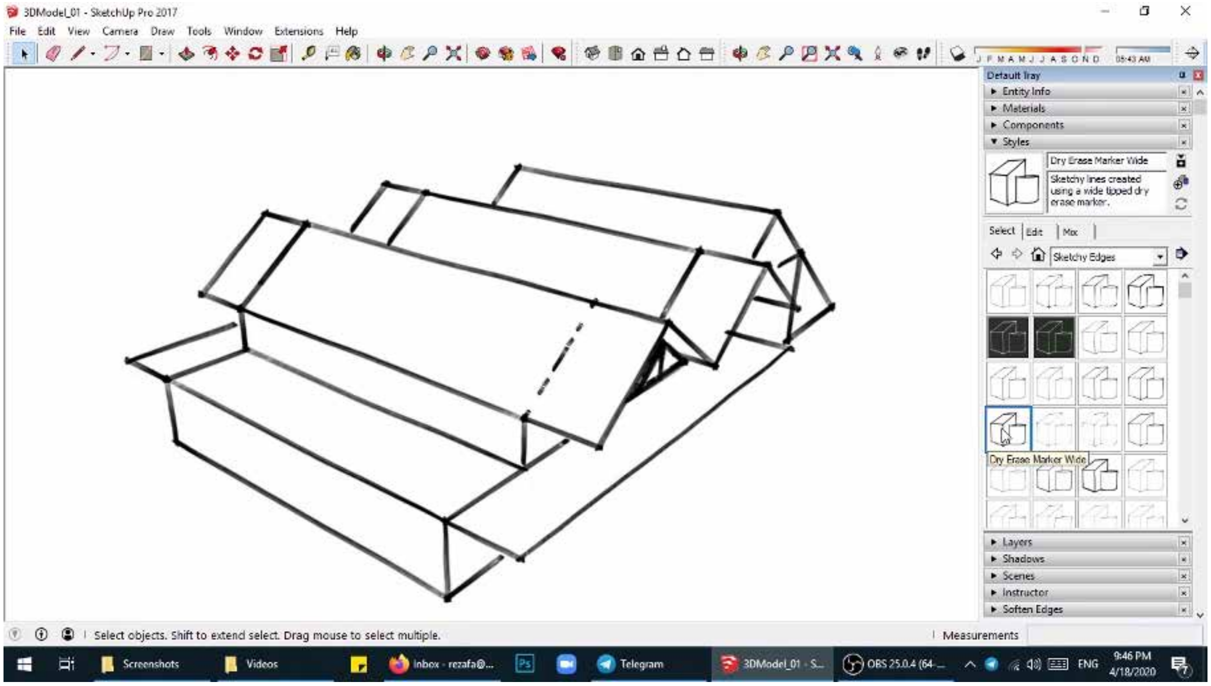


Figure 6-6 A screenshot from the video demonstrating the styles feature in SketchUp

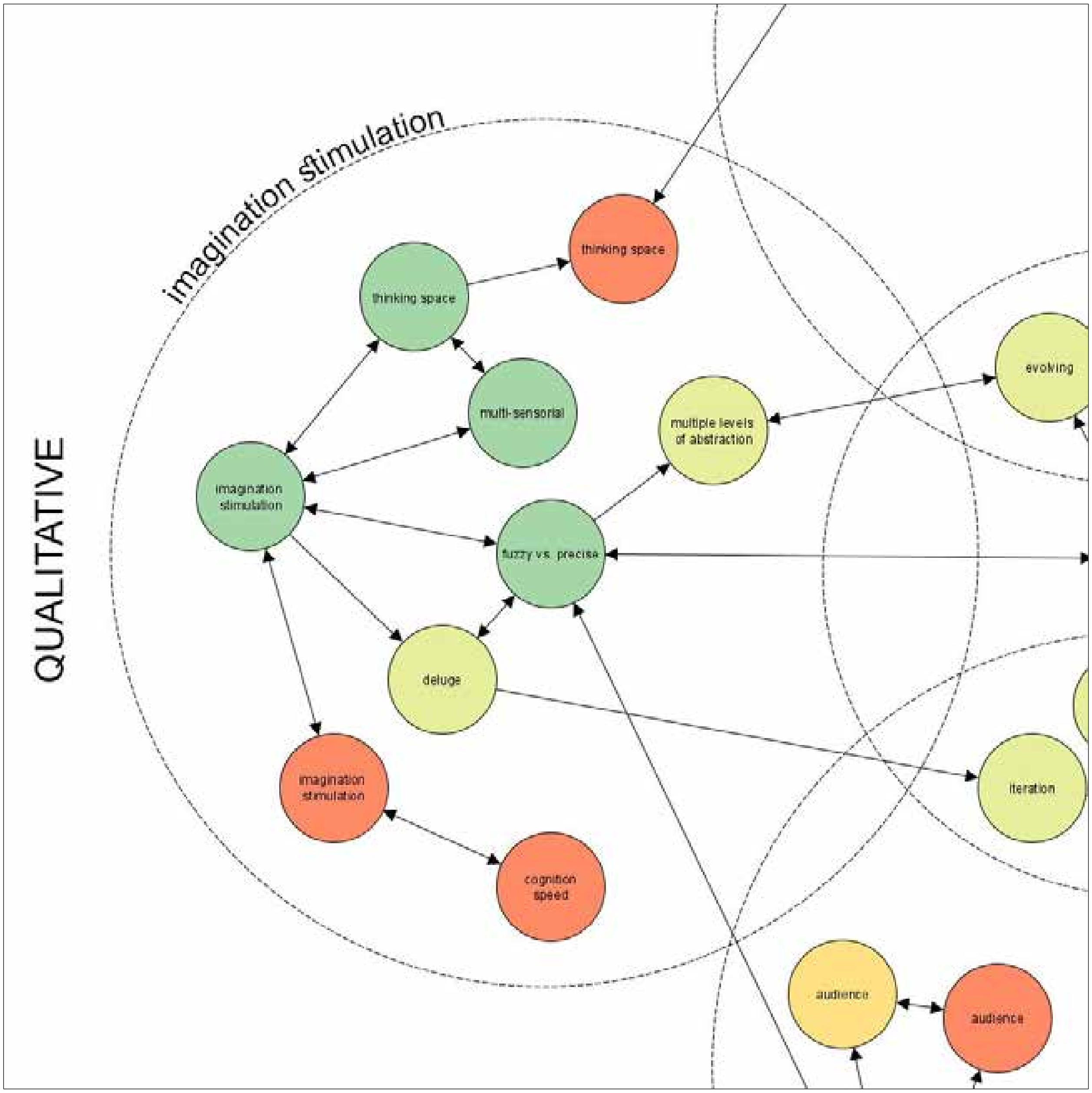


Figure 6-7 Imagination Stimulation sub-themes

6.3.2. Knowledge Acquisition

This page provided a list of *Knowledge Acquisition* sub-themes (Figure 6-9) which discuss:

Simultaneous Learning: introduction of digital tools, along with manual tools, early on while students are simultaneously learning design skills and techniques, where technique often includes the proper utilization of the tool

A priori Knowledge: providing the required *a priori* knowledge that is necessary for the proper utilization of the tool

Understanding Outputs/Validation: providing the required knowledge to understand and validate the outputs of digital tools that are used for quantitative studies

Frameworks: developing decision-support frameworks

Pedagogic Tools: the ability of the design environment to provide the user with the required knowledge (Figure 6-8)

Timing: the ability of the design environment to provide/request the proper amount of information based on the design stage

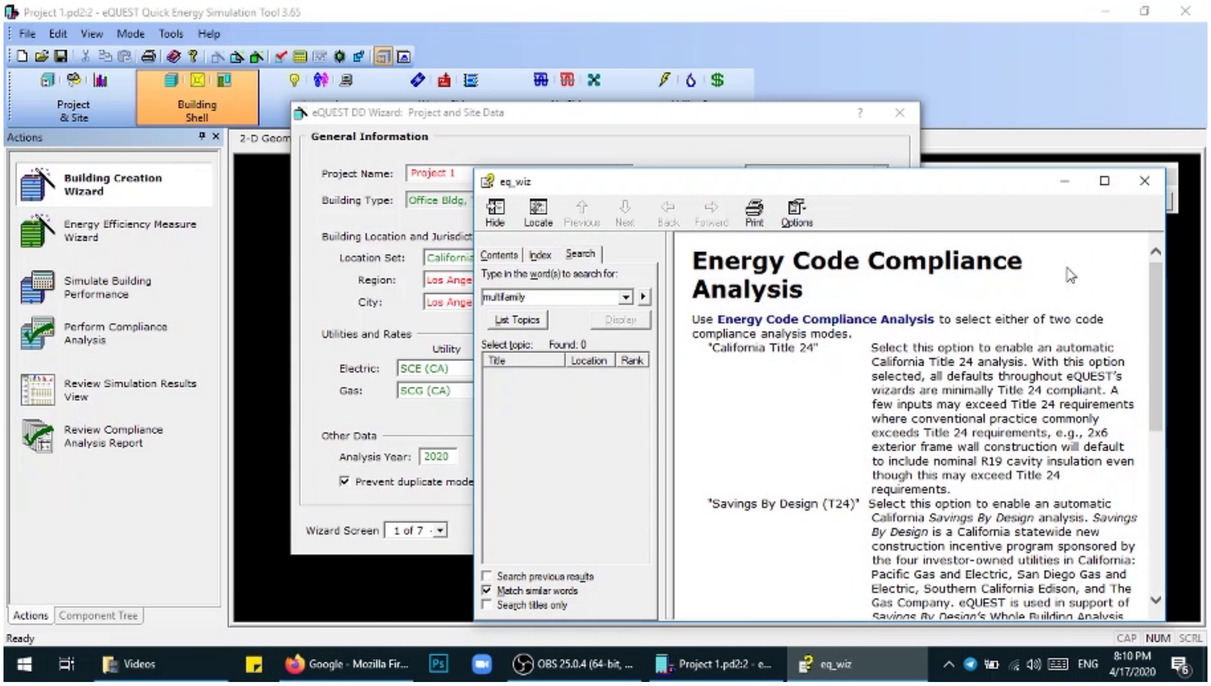


Figure 6-8 A screenshot from the video demonstrating inputs help feature in eQuest as an example of a pedagogic tool

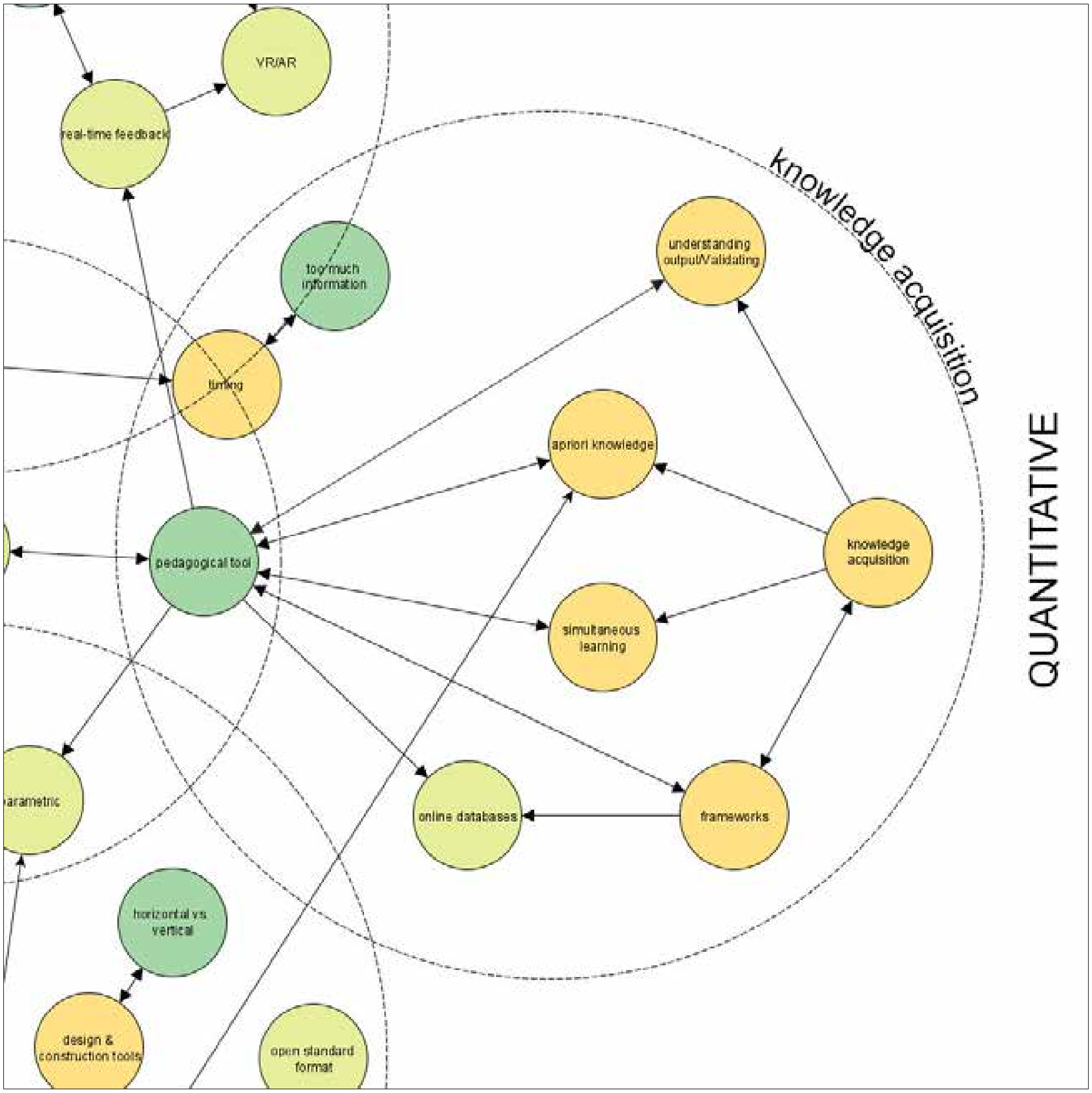


Figure 6-9 Knowledge Acquisition sub-themes

6.3.3. Hybrid Environment

This page pointed out that the concept of hybrid design environments is to question dualities such as digital versus manual tools and to advocate for a design environment that simultaneously supports:

Manual and digital tools (Figure 6-10 and Figure 6-11)

Physical and virtual representations

Inside and outside (immersive and non-immersive) studies

This page also pointed out that a key goal of a hybrid design environment is to provide *real-time feedback* for both qualitative and quantitative studies. (Figure 6-12) Also, an important area of development for supporting such real-time feedback is the application of *Virtual Reality (VR) and Augmented Reality (AR)* tools. (Figure 6-13) For the outline of the sub-themes please refer to Figure 6-14.

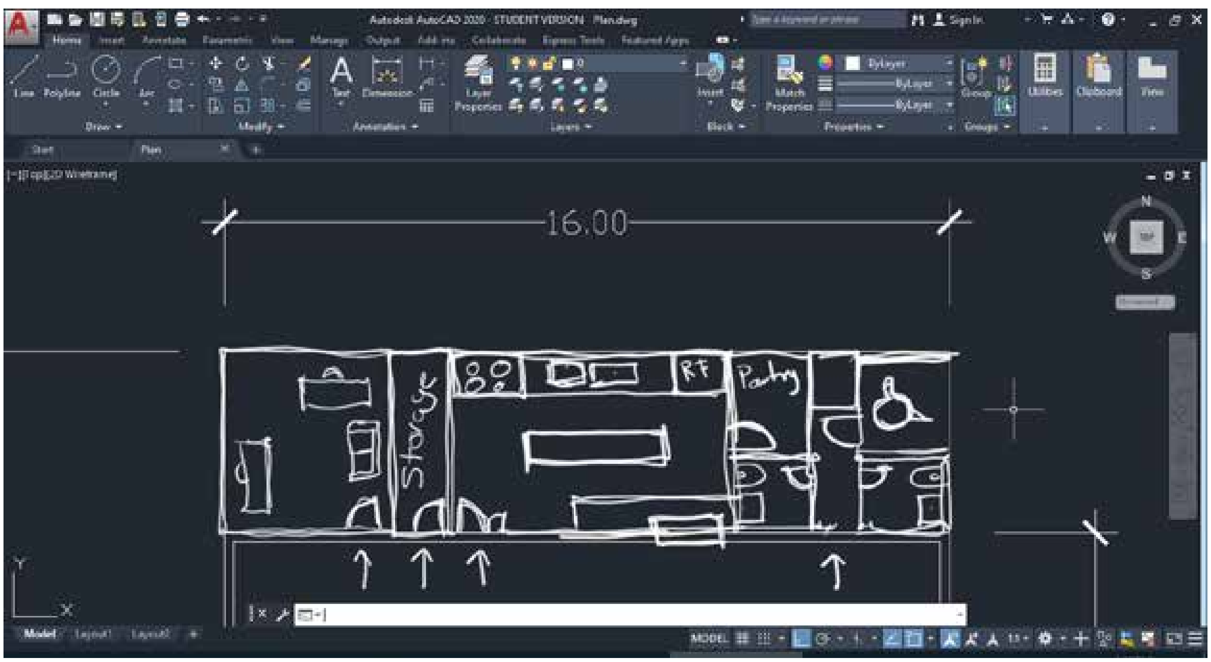


Figure 6-10 A screenshot from the video demonstrating hypothetical sketching capabilities inside AutoCAD

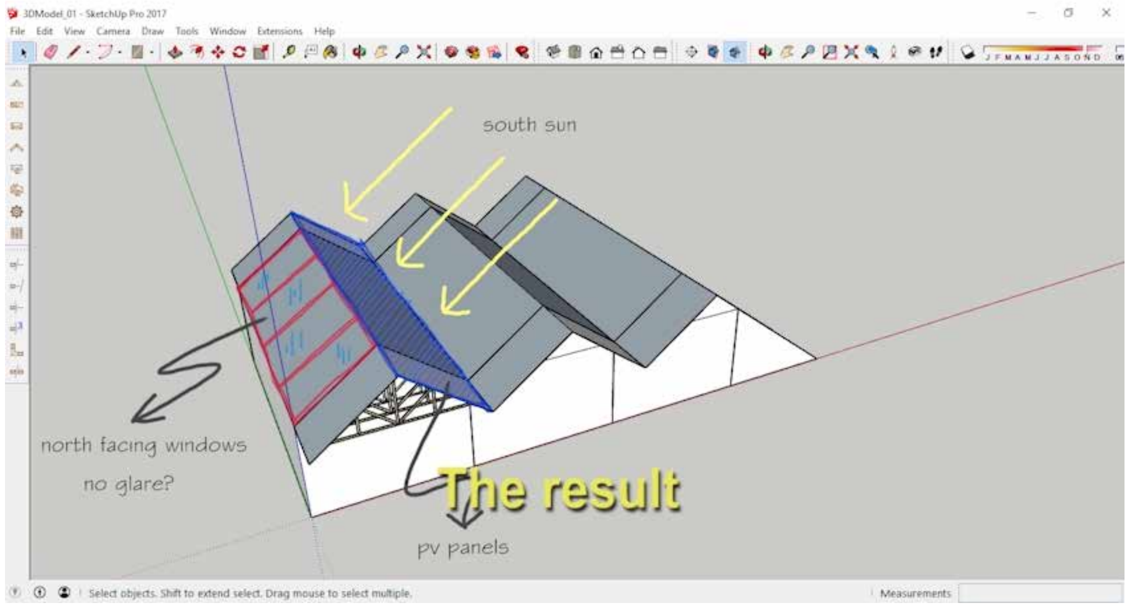


Figure 6-11 A screenshot from the video demonstrating hypothetical sketching capabilities inside SketchUp

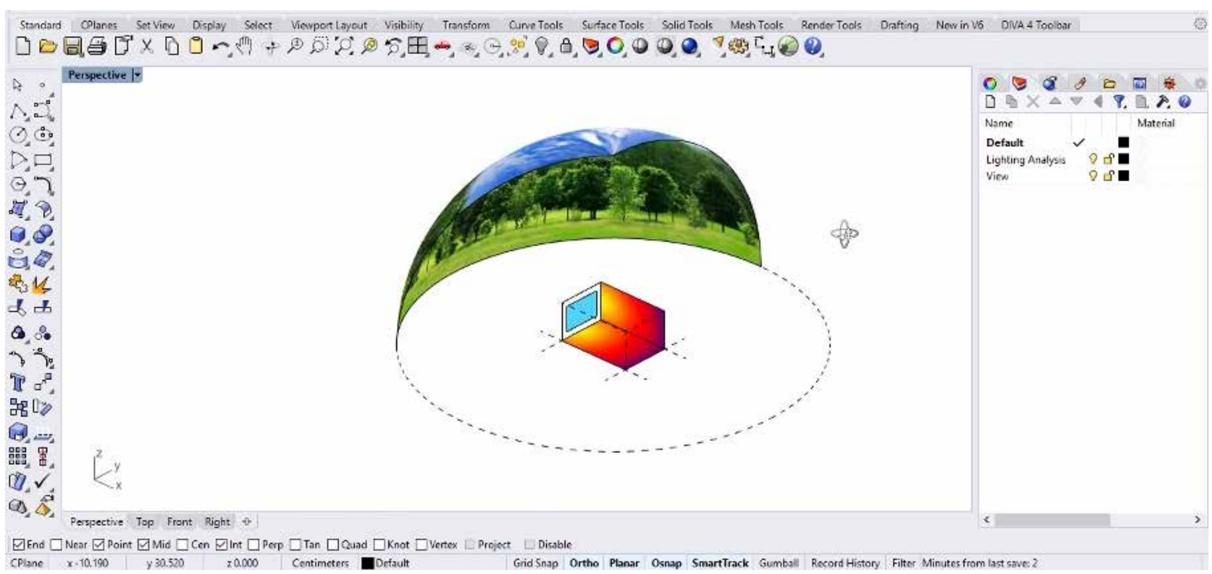


Figure 6-12 A screenshot from the video demonstrating hypothetical real-time feedback feature for view and daylight in Rhino

Figure 6-13 A screenshot from the video demonstrating interior study of the design using VR through Modelo

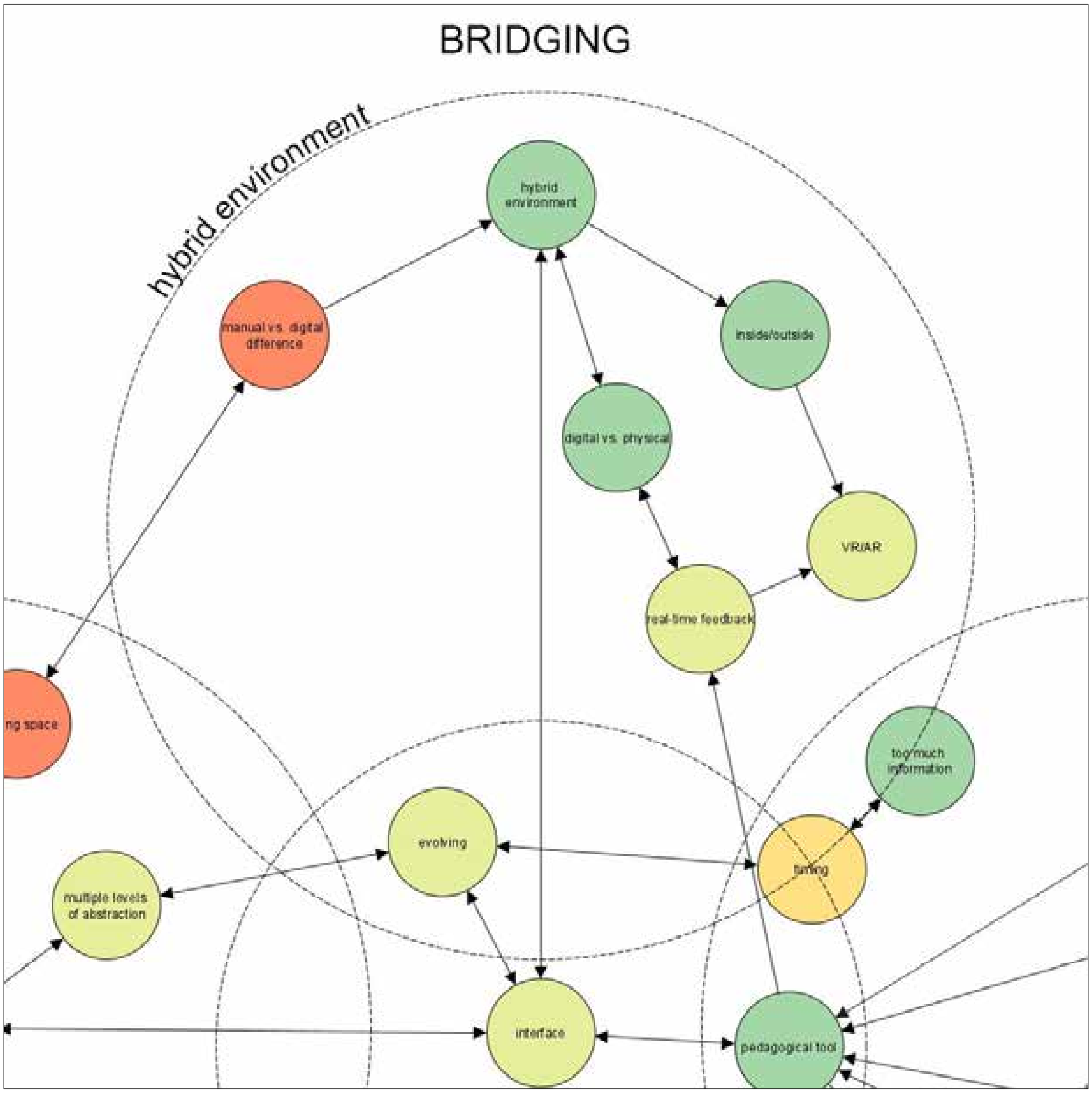


Figure 6-14 Hybrid Environment sub-themes

6.3.4. Architect as Toolmaker and Design Environment Coordinator

This page pointed out that the concept of the architect as toolmaker and design environment coordinator does not necessarily mean that the architect or the architecture community would be developing tools such as computer software, but rather it means that the architect should be the person who connects various tools together and creates a unique constellation of tools in order to define the design problem. (Figure 6-15)

It added that this approach reinforces the *architect's control* over the design process. It also supports *dialogue* during the design process, both internal (architect with him/herself) and external (with different audiences and parties involved in the design project). (Figure 6-16)

Additionally, this approach requires *architecture community involvement* to:

1. Provide their intuitive knowledge about design and construction
2. Balance the power dynamic which exists in current economic models

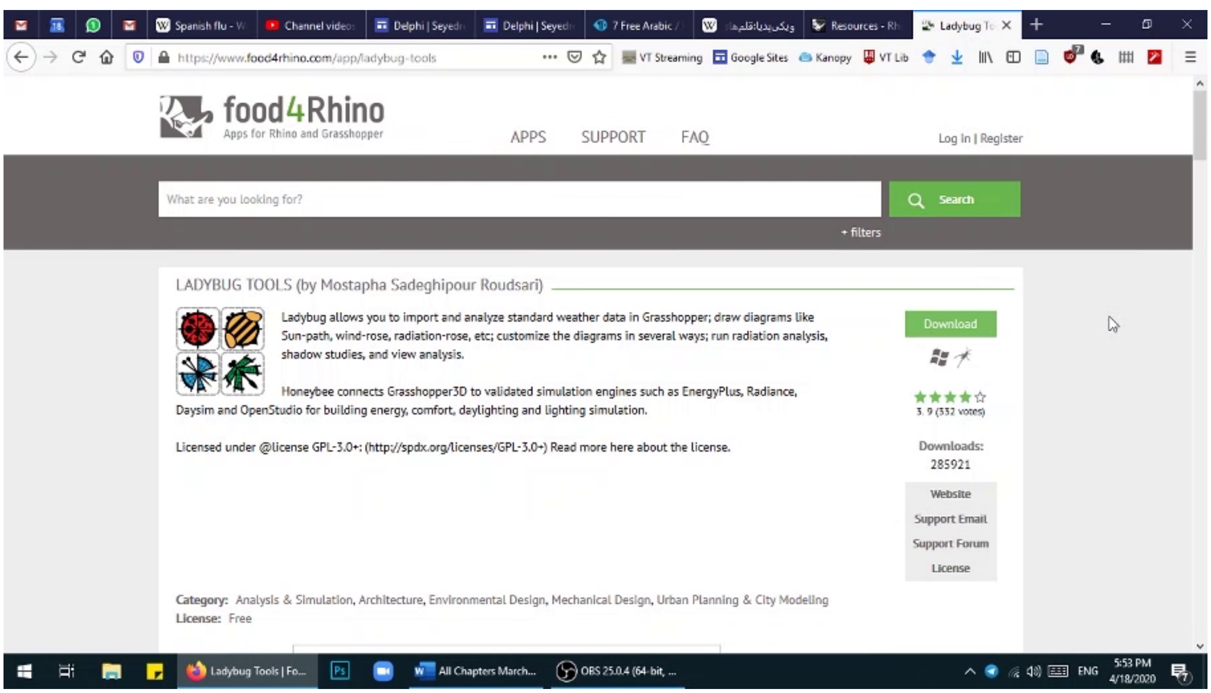


Figure 6-15 A screenshot from the video demonstrating Rhino and Grasshopper plugin platform (food4Rhino) as an example of a feature supporting the concept of the architect as toolmaker and design environment coordinator.

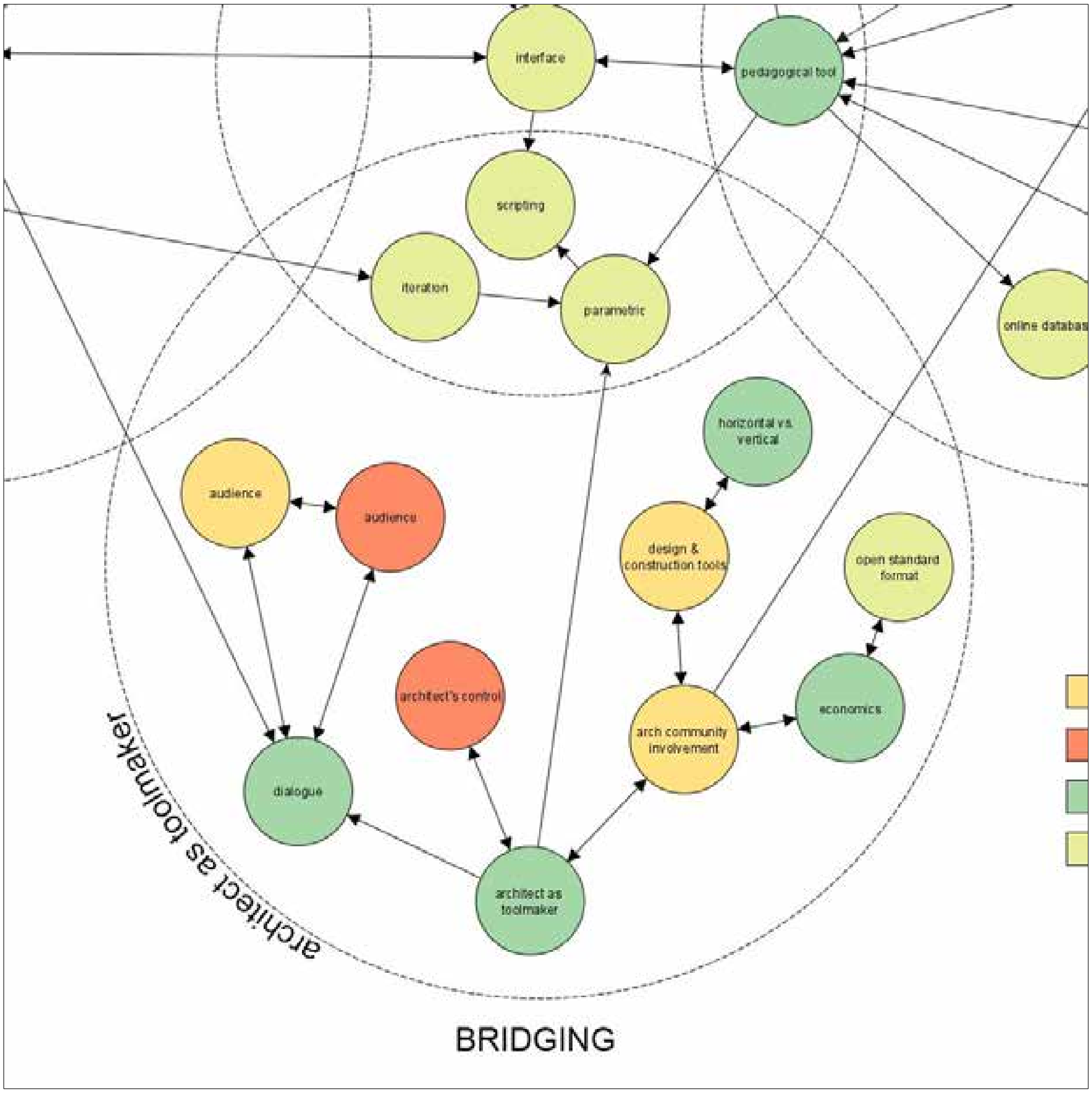


Figure 6-16 Architect as toolmaker and design environment coordinator sub-themes

6.4. The Report

The report of the first round of the Delphi panel which was used during the second round consisted of two sections. The first section discussed suggestions by the participants during the first round. The second section consisted of the questions the participants raised and my answers to them.

6.4.1. Suggestions

Participants #1 and #6 suggested the inclusion of "computational multi-criteria optimization algorithms" in the framework. Participant #1 pointed out that:

> *"A major method that was not currently included in your discussion of the framework is the computational method of multi-objective optimization (or multi-criteria optimization). The optimization framework is established, including the identification of building parameters, performance simulation and analysis, fitness functions, optimization algorithms, and post-optimization evaluation. In terms of qualitative criteria, if they cannot be quantified and modeled in a computer model (which can be argued, e.g., for the View criterion you proposed), then architects and/or users' preferences may become part of the optimization process."*

I did an initial investigation into optimization algorithms during the literature review and certain themes such as *architect's control* developed directly as the result of that investigation. (refer to 2.5 Qualitative and Quantitative Criteria During the Design Process) Other themes such as *framework*, *pedagogic tool*, and *real-time feedback* are also closely related to this topic. (Figure 6-17) To illustrate these connections, we need decision-making frameworks that, as suggested by participant #1, define the parameters and fitness functions as comprehensively as possible. Then we need pedagogic tools that incorporate performance simulation and analysis engines as well as optimization algorithms and can provide real-time feedback to the architect for evaluation and iteration.

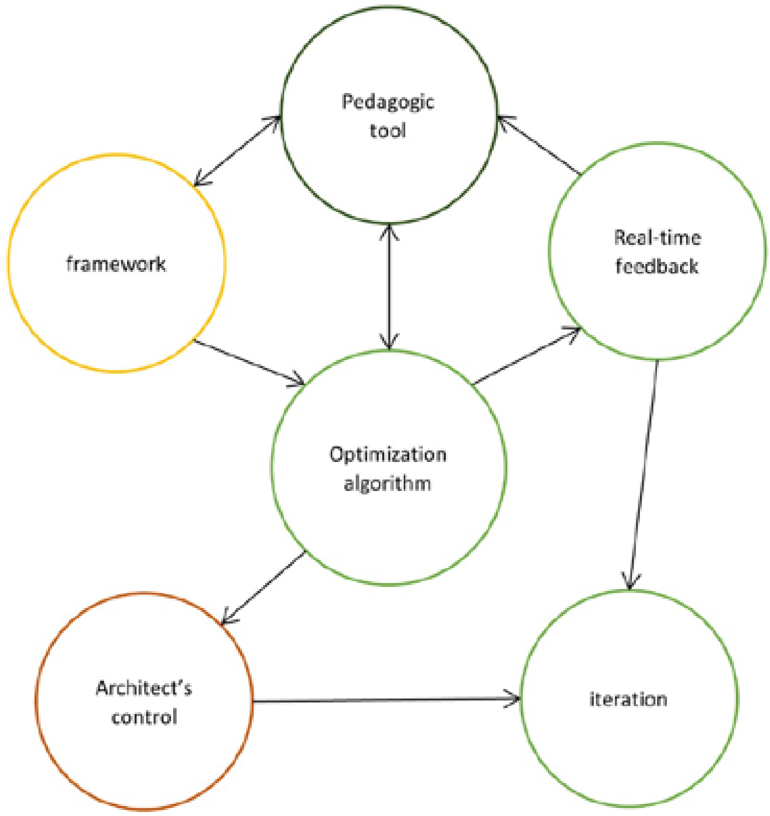


Figure 6-17 The Optimization Algorithm theme and its neighboring themes

In other words, the optimization algorithms can become a mediator between raw data produced by performance simulation engines and the user. They can provide the user with suggestions and design guidelines based on simulation results. Such features would enhance the pedagogic capabilities of the tools. (Figure 6-18)

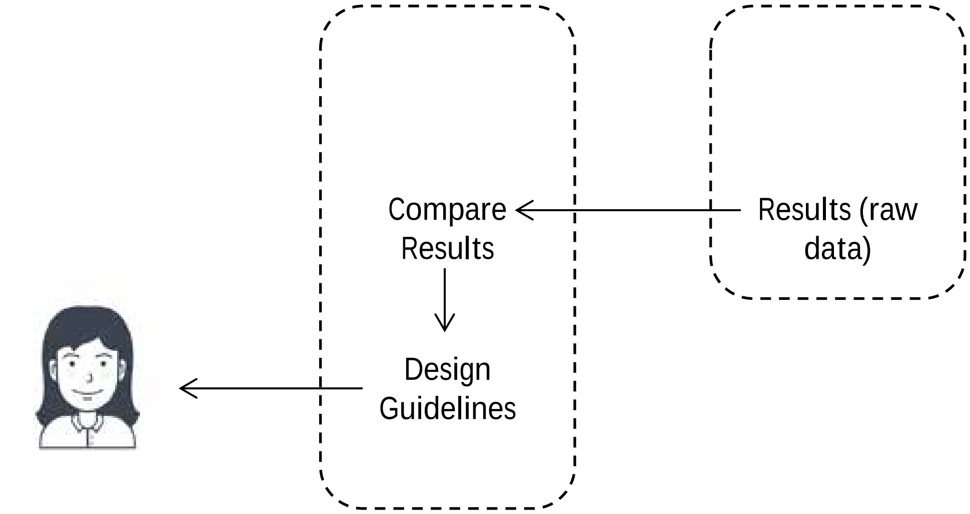


Figure 6-18 Optimization Algorithms as a mediator between the user and performance simulation tools

Participants #2 and #4 suggested a diagram for mapping each tool within the framework. An initial draft of this diagram for mapping tools as I have used them during the immersive case study was developed. (Figure 6-19)

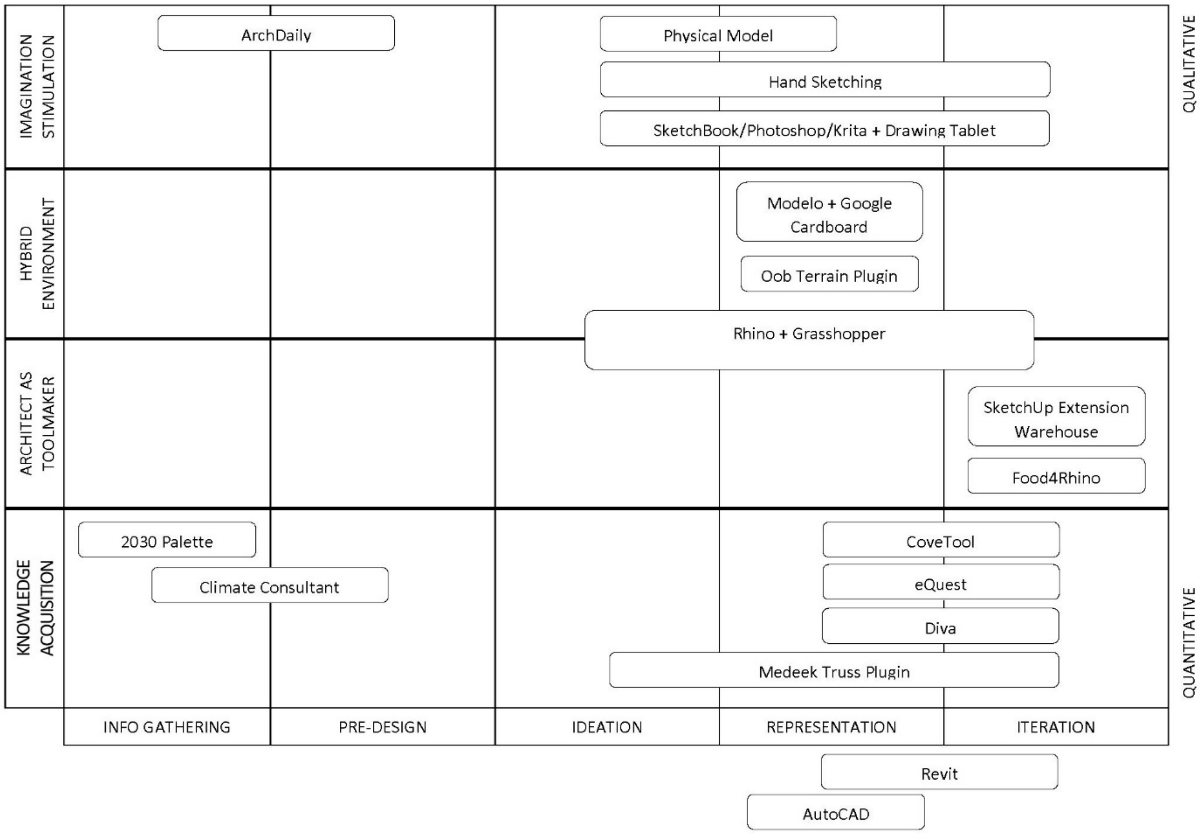


Figure 6-19 Mapping tools within the framework

Participant #2 suggested that the *Hybrid Environment* theme can be seen as a part of the more overarching *Architect as Toolmaker* theme. He pointed out:

> *"Your framework Venn diagram in the results section implies that the Architect as a Toolmaker is disjoint from the Hybrid Environment, even though the architect uses such environment via the Interface presented later. I understand this two-stage logic but wonder if instead the Architect as a Toolmaker is a much larger, encompassing entity."*

Therefore, as suggested by participant #2, the framework can be modified based on this new categorization. (Figure 6-20)

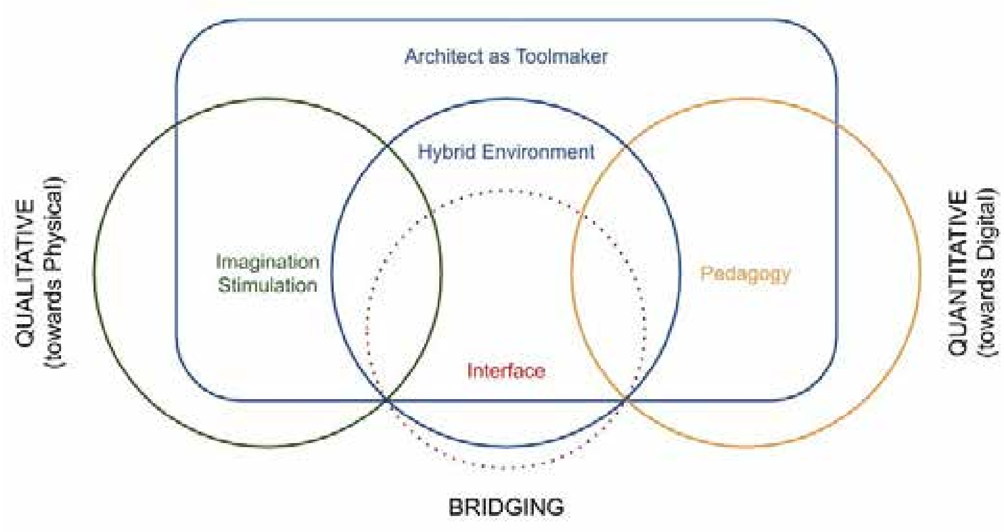


Figure 6-20 A new arrangement of the main themes suggested by participant #2

Participant #2 suggested adding site visit as a tool to the *Imagination Stimulation* theme in general, and the *multi-sensorial* theme in specific. (Figure 6-21) He suggested:

> *"An important tool/feature to also highlight…, in my opinion, and experience, is an actual site visit to the specific project location. I recommend a first-person physical analysis of the view and glare during that specific moment and/or set of moments. You likely have this under your "multi-sensorial" element. Are there specific vistas or vantage points (i.e., qualitative aspects) that would be difficult to capture through only quantitative and/or digital analysis? Do any other sensory stimuli impact views and glare (e.g., wind in the distance affecting the sound of leaves on trees and therefore capturing more attention to a particular view that a plane field without sounds, or flowing water with persistent noise drawing major attention to it and making one realize ever-changing glare on its surface that a photograph would have not captured)?"*

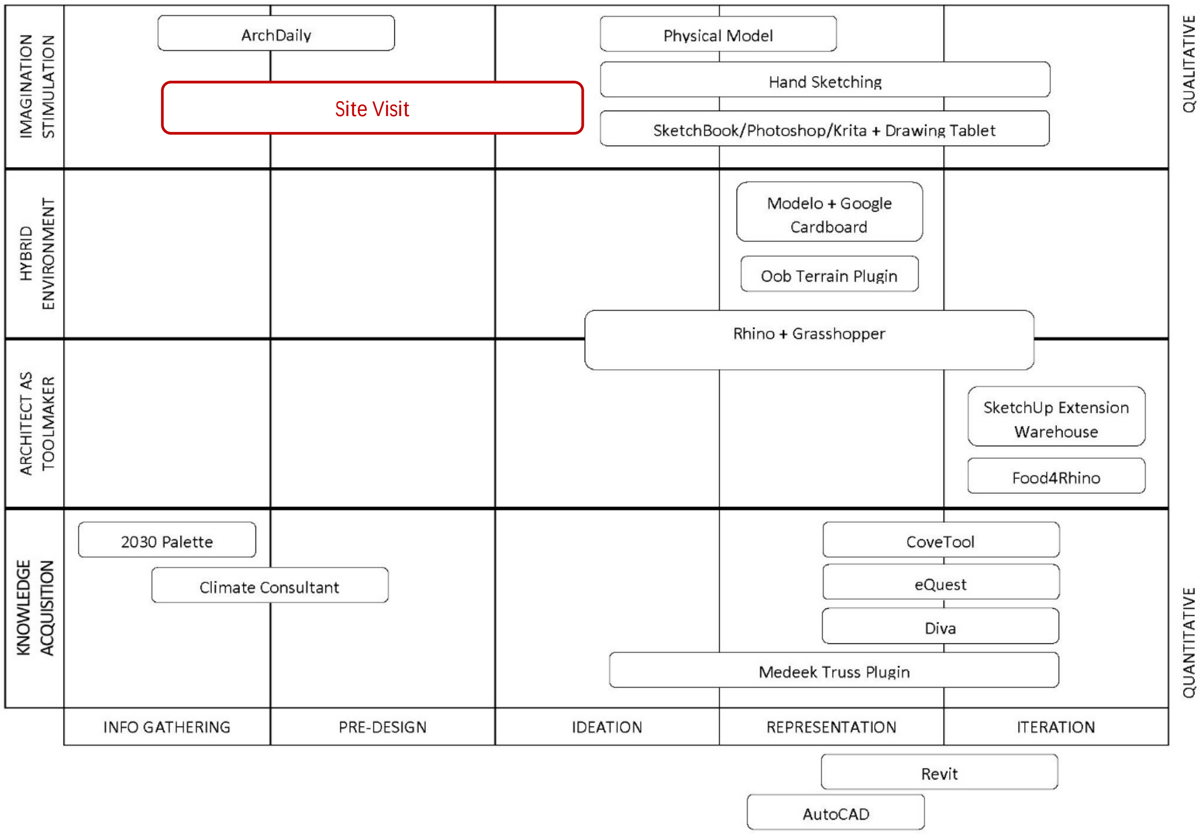


Figure 6-21 Adding Site Visit as a tool

6.4.2. Questions

This section of the report provided a list of the questions that were raised by the participants during the first round of the Delphi panel and my answers to them:

1. Participant #4: Can you provide more information on the Cove Tool (such as the theoretical background of the tool)?

CoveTool (https://www.cove.tools/) is an online and cloud-based energy analysis platform. It uses energy calculations defined by ISO 13790 and CEN 15603 and is one of the tools suggested by the 2030 Palette (http://www.2030Palette.org/).

2. Participant #4: In the framework, *knowledge acquisition* is categorized under quantitative knowledge. However, there is a knowledge acquisition to support students to qualitatively understand their projects in architecture programs. Did you exclude these parts because only a knowledge acquisition for quantitative knowledge is the scope of your work in this study or because you believe that educational efforts for quantitative knowledge are missing in the current architectural education system?

The latter. The *knowledge acquisition* subthemes that emerged during the interviews and the immersive case study, mostly discuss the limitations of the current architecture curricula and tools in providing the architects with the required knowledge to perform quantitative analyses such as glare analysis.

3. Participant #2: In what way do your *knowledge* and *cognition* themes differ from each other?

The cognition themes discuss topics that relate to cognitive processes, i.e. mental processes involved in the acquisition, storage, interpretation, manipulation, transformation, and use of knowledge. (*Cognitive Process*, n.d.) For instance, the *audience* as a subtheme of the *knowledge* theme discusses the different sets of knowledge various parties involved in the project (the architect, the mechanic engineer, etc.) require or possess. While the *audience* as a subtheme of the *cognition* theme discusses how various parties involved in the project interpret the outputs produced by the tool.

6.5. Summary

The Delphi panel consisted of two rounds of communications with the panel of experts. At the end of the second round, all participants (100%) indicated that they find the framework applicable in its current state. The Delphi panel helped to finalize the framework and establish the credibility of the findings. The following figures represent the finalized framework as the outcome of this step. Figure 6-22 provides a detailed overview of the framework.

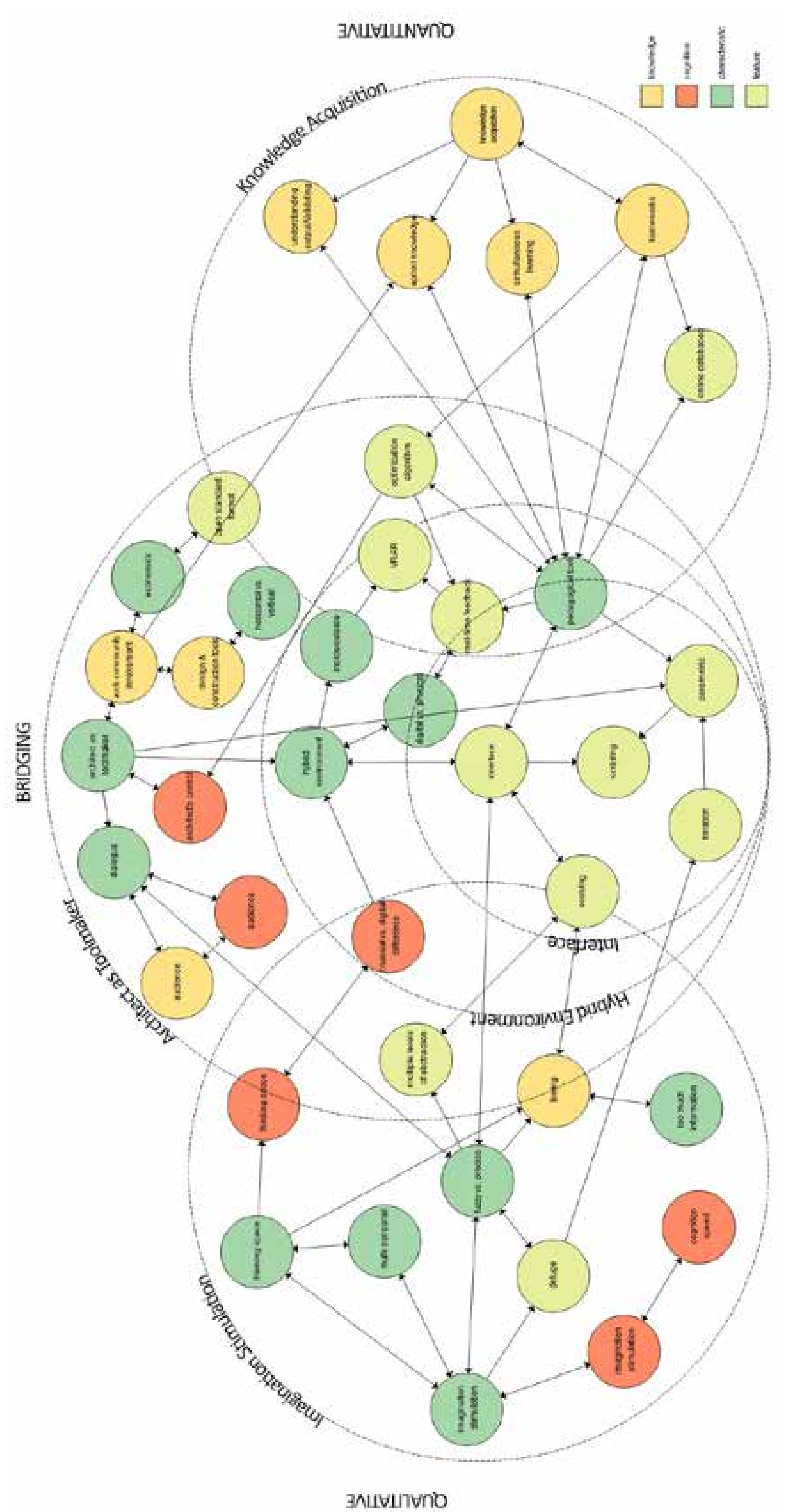


Figure 6-22 The finalized framework at the end of the Delphi method stage

Figure 6-23 represents the framework and the themes as they relate to the design process stages.

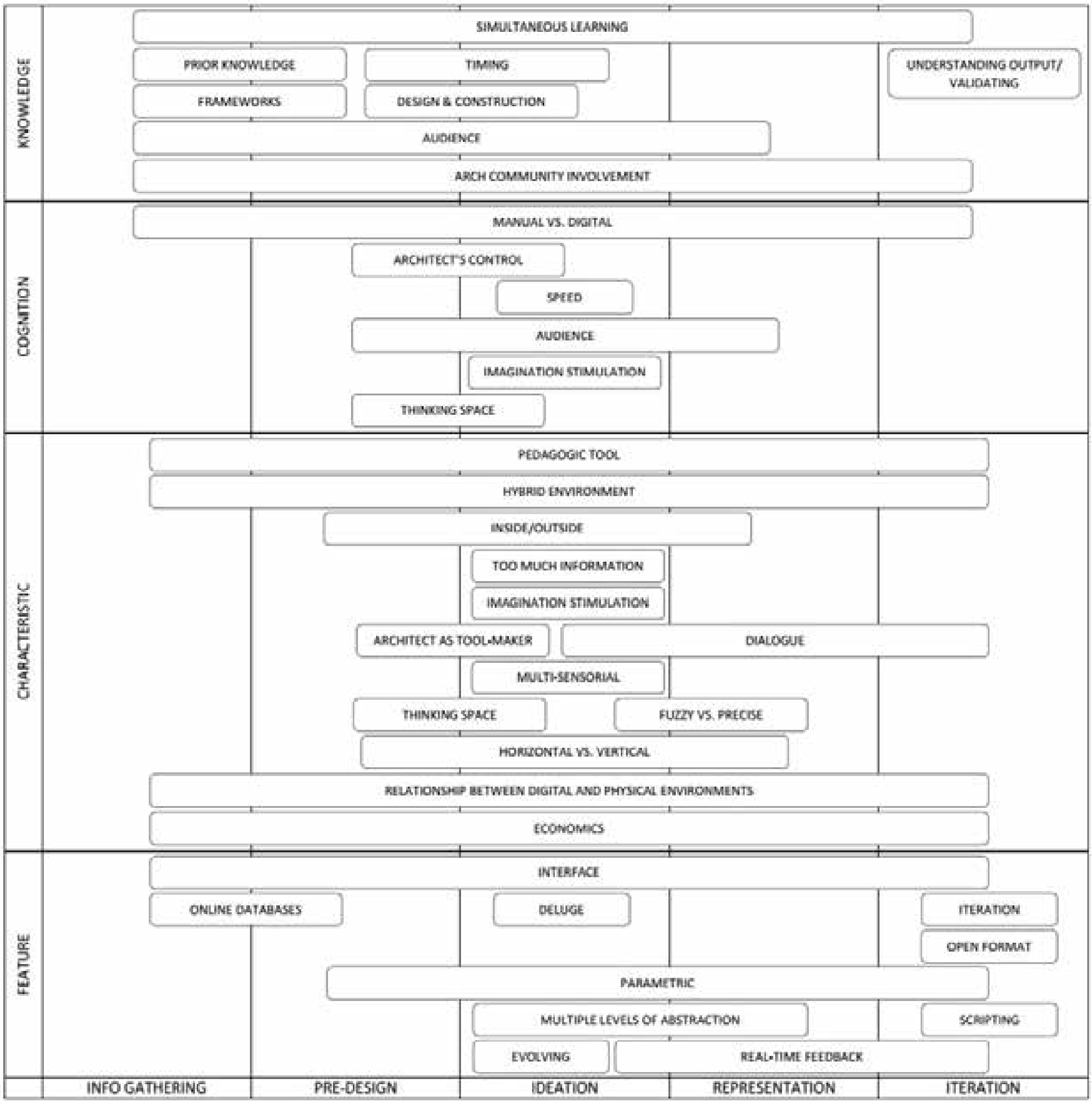


Figure 6-23 Representation of the framework based on design process stages

Figure 6-24 represents the tools that were used during the immersive case study as they relate to the design process stages. This figure was added to the framework by the suggestion of the participants through the Delphi panel process.

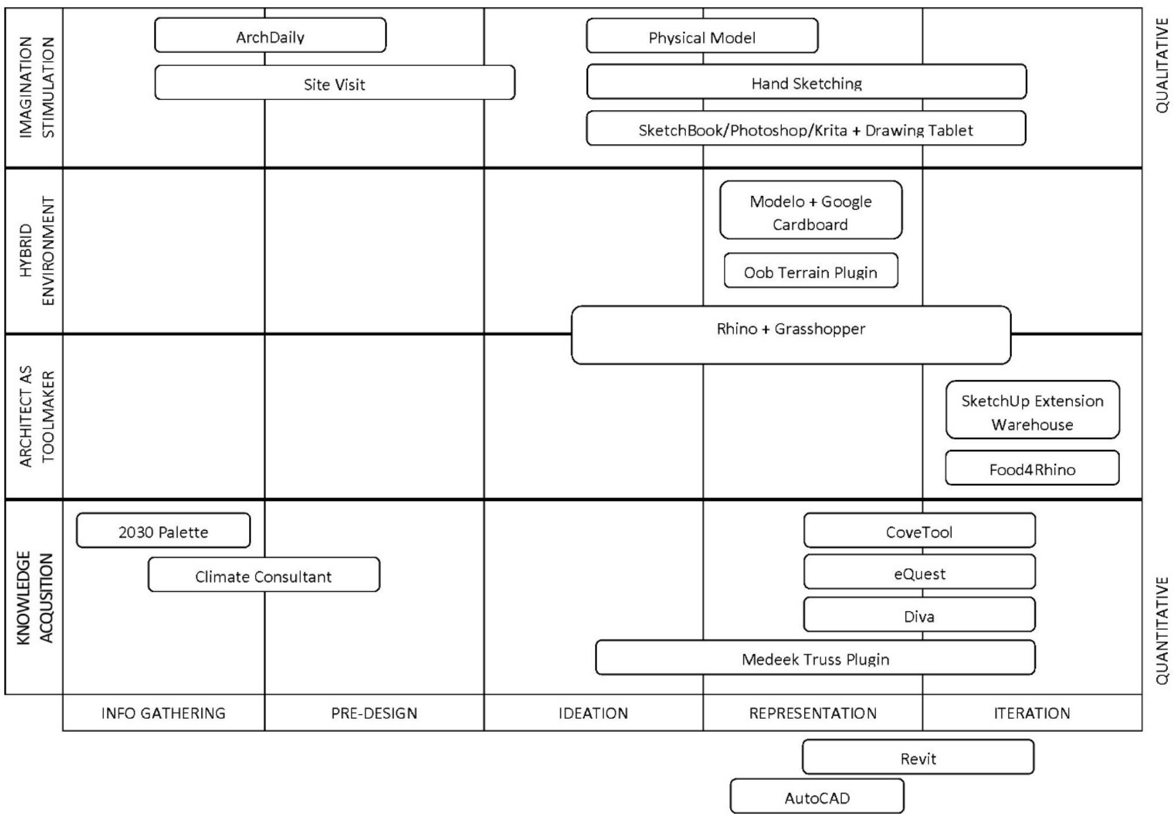


Figure 6-24 Tools used during the immersive case study in relation to the main themes and the design process stages

7. Conclusion

7.1. Introduction

This chapter serves as the final chapter of this dissertation and presents the finalized framework as the outcome of the Delphi panel stage, discussed in the previous chapter. It also provides a more coherent discussion of the themes as they relate to one another. Throughout this chapter, references to chapters four and/or five are mentioned after discussing each theme. These references provide the reader with more details and examples.

7.2. Research Summary

This research started with the question: how can architects simultaneously address qualitative and quantitative criteria during the design process? This led to the investigation of the available literature, documented in Chapter 2. This investigation had two objectives:

1. Calibrating the research question.
2. Designing the appropriate methodology to approach the research question.

As the result of this stage, the research question was formulated as: What are the features and characteristics in an architectural tool that support simultaneously addressing qualitative and quantitative criteria during the early stages of the design process?

Also, a methodology consisting of four steps was proposed (refer to chapter 3). The first step was logical argumentation based on the literature review. This step was used to define the main areas of investigation and develop the initial themes. These themes were further investigated and expanded during the second step, the interviews. (refer to Figure 4-25 for a visual representation of the themes that emerged during each of these two steps and the expansion of the framework.) Six interviews were conducted in total. The process and the results of the interviews are documented in Chapter 4.

Chapter 5 documents the third step. The immersive case study was used to provide more details and depth to the framework. The prior steps provided a foundation to decide about the tools and the areas to be investigated during the immersive case study. A detailed log of all the studies and the experiences was kept during this step. This log was used as the source of the data for analysis.

As the final step, the Delphi method was used to finalize the framework, expand the member checks, and demonstrate consensus and credibility. The Delphi panel consisted of seven participants and the process and the results are documented in Chapter 6.

7.3. The General Structure of the Framework

The framework tried to create a bridge, spanning the gap between qualitative and quantitative studies during the early stages of the design process. The framework resembles the general structure of a bridge which consists of three main elements: two foundations on each side and the deck spanning between them. Similarly, the framework categorizes the themes in three main areas: the themes concerned with qualitative studies, the themes concerned with quantitative studies, and the themes concerned with bridging the gap between qualitative and quantitative studies. The framework suggests that four major themes need consideration while developing architectural tools to support simultaneously addressing qualitative and quantitative criteria (Figure 7-1):

1. For quantitative studies, such as glare analysis, a more robust knowledge acquisition strategy is needed.

2. For qualitative studies, such as view study, the role of the tools as a stimulus of imagination should be emphasized.
3. For bridging the gap between qualitative and quantitative studies, the role of the architect as toolmaker and design environment coordinator should be emphasized. It does not mean that the architect should be the developer of the tools but rather the architect should be the person who connects various tools and thus creates a unique constellation that helps to define the design problem from a certain perspective.
4. For bridging the gap between qualitative and quantitative studies, the design environment (the constellation of the tools and methods used by the architect) should be a hybrid environment, one that includes both manual and digital tools, immersive and non-immersive digital representations, etc.

The central feature that connects all these themes is the interface of the tool (Figure 7-1) and its ability to support two processes:

1. The iteration stage during the design process
2. The ability of the interface to evolve and correspond to the demands and characteristics of different stages of the design.

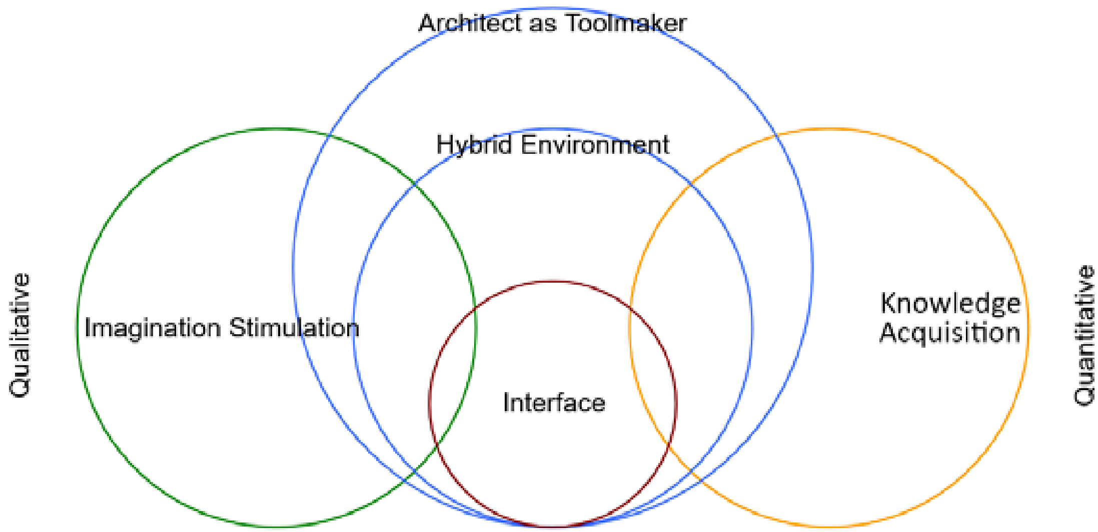


Figure 7-1 The general structure of the framework

Figure 7-2 represents a detailed version of the framework. It includes all the sub-themes that are discussed as part of the major themes mentioned above. The emphasis of this diagram is on representing the thematic relations between the themes.

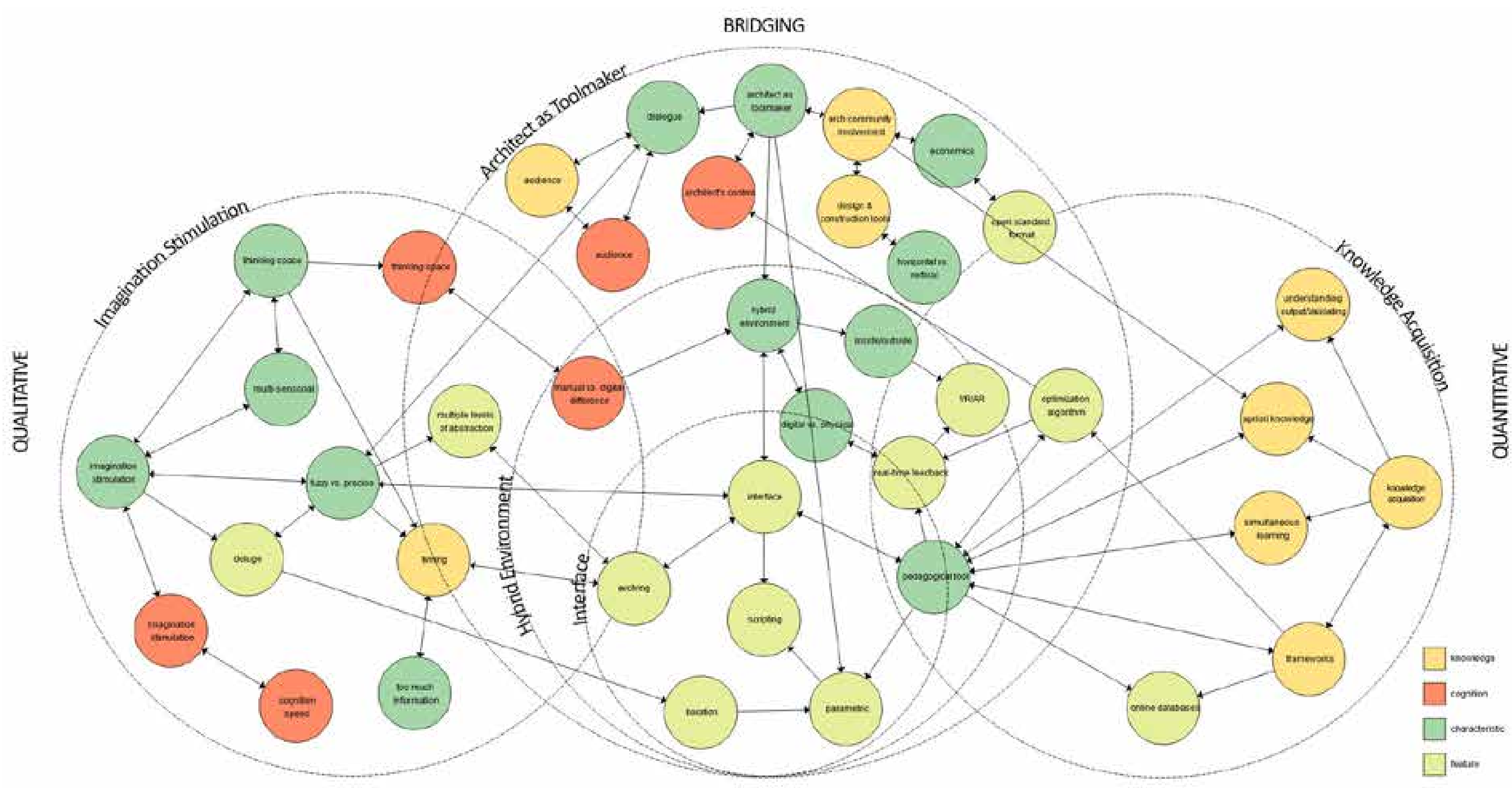


Figure 7-2 The detailed version of the framework

The framework also categorizes the sub-themes based on the design process stages. Figure 7-3 represents the framework from this perspective. The horizontal axis of this matrix represents the design process stages while the vertical axis represents the areas of inquiry.

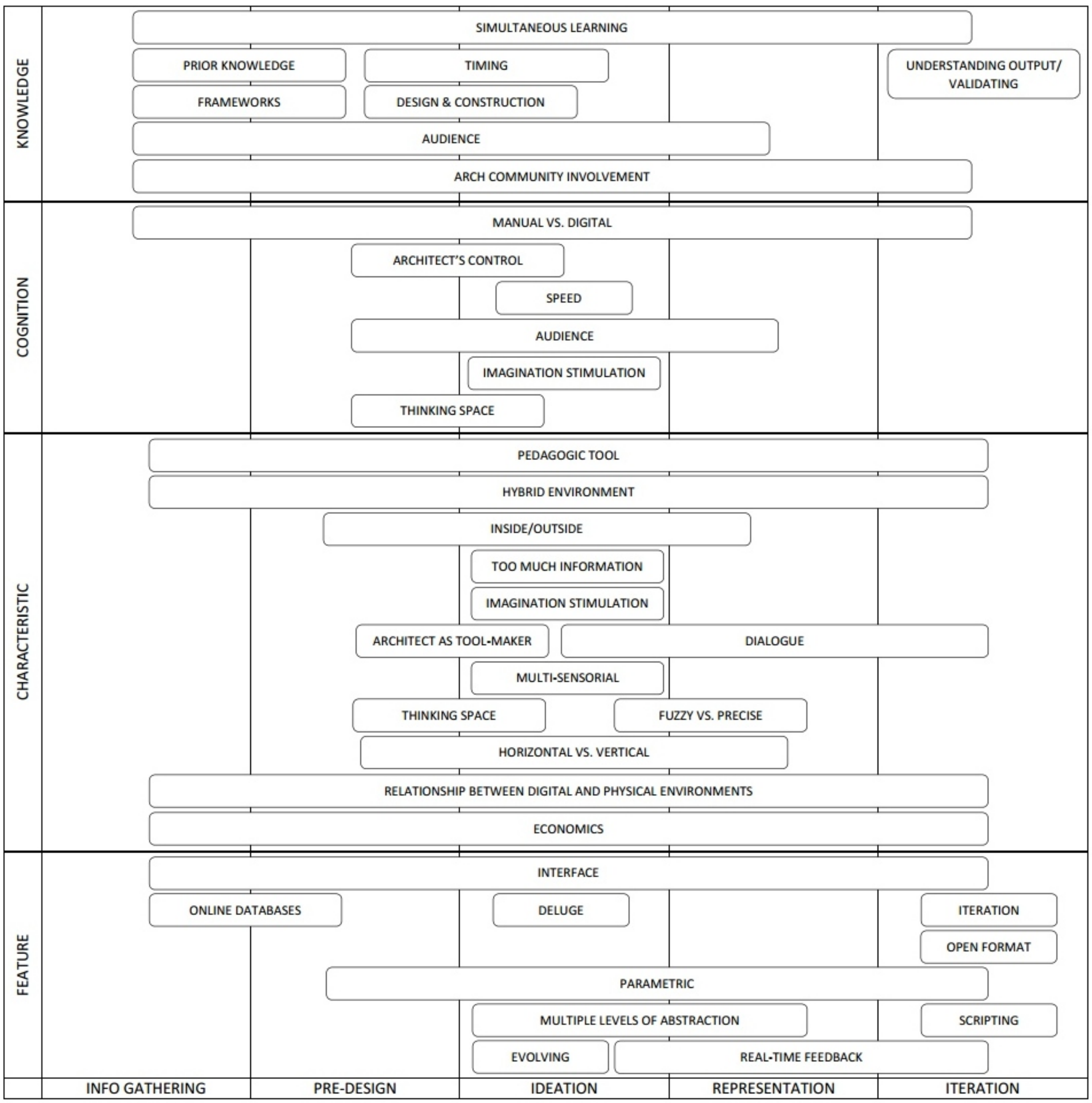


Figure 7-3 Framework representation based on design process stages

Additionally, the framework categorizes the tools which were used as part of the immersive case study step based on the design process stages. (Figure 7-4) The horizontal axis of this matrix represents the design process stages while the vertical axis represents the major themes of the framework.

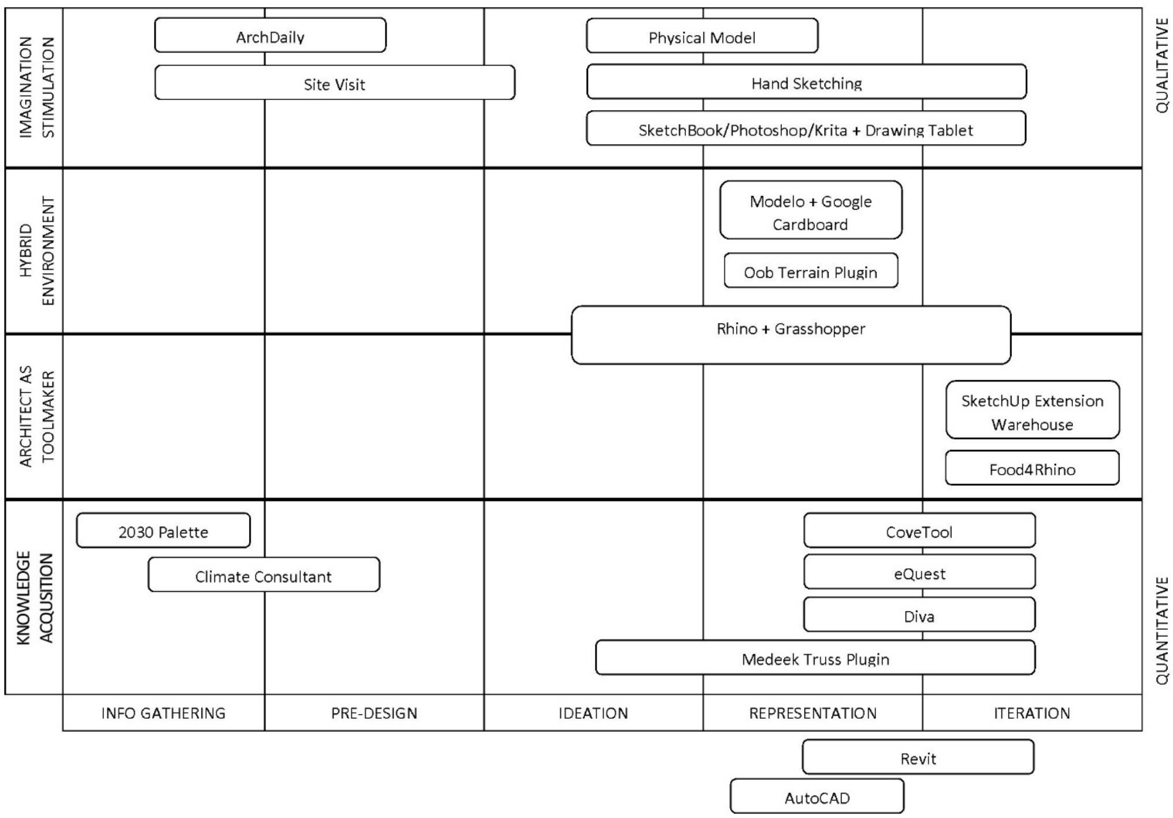


Figure 7-4 Framework's representation of the tools based on design process stages

Table 7-1 provides a generic version of the similar table that was produced during the immersive case study. It represents a timeline of common design tasks that are performed during the early stages of the design process. For each task, it provides the objectives as well as the tools which may be used to achieve them for both qualitative and quantitative aspects of that task. Also, the table connects this information to the framework by providing the themes that address each task and suggesting strategies for qualitative and quantitative synthesis.

Table 7-1 Early stages of the design timeline and the qualitative and quantitative synthesis strategies

Design Task	Qualitative		Quantitative		Framework Themes	Qualitative and Quantitative Synthesis
	Objectives	Tools	Objectives	Tools		
Info gathering / Program development	Required spaces / Spatial relations and qualities	Time-Saver Standards / Google Images / ArchDaily	Required areas / Code requirements	Time-Saver Standards / Building code websites	*A priori* knowledge / Online databases / Architecture community involvement	Developing databases and frameworks with multiple layers of information
Pre-design / Context	Site study	Google Earth	Climate study	Climate Consultant	Frameworks / Online databases / Timing / Pedagogic tool	Overlaying qualitative and quantitative information
Pre-design / Inspiration	Formal inspiration	ArchDaily / PureRef	Design guidelines and strategies	2030 Palette / Climate Consultant	Frameworks / Timing / Pedagogic tool	Creating physical or digital boards including examples
Ideation / Presentation / Massing	Concept / Form generation	Hand sketching / Physical modeling	Incorporation of design guidelines and strategies	Hand sketching / Physical modeling / SketchUp	Fuzzy vs. Precise / Multiple levels of abstraction	Sketching over drawings or images
Design Development / Energy model			Orientation and Window to Wall Ratio (WWR)	eQuest / CoveTool	Evolving / Interface / Understanding and Validating Output / Timing / Architect's control / Real-time feedback / Audience / Pedagogic tool	Energy, daylight and view real-time feedback / Various roles working on the model and using 3D comments for communication
Design Development / Plan Development	Developing the spatial relations	Hand Sketching / Drawing tablet / Photoshop	Developing a scaled plan	AutoCAD	Hybrid environment	Hand sketching in the AutoCAD environment

Design Task	Qualitative		Quantitative		Framework Themes	Qualitative and Quantitative Synthesis
	Objectives	Tools	Objectives	Tools		
Design Development / 3D model development	Studying the spatial characteristics / Developing details	SketchUp / Medeek Truss and Oob Terrain plugins	Developing a 3D model for advanced energy and daylighting analysis	SketchUp / Rhino	Thinking space / Architect as Toolmaker / Fuzzy vs. Precise / Real-time feedback / Pedagogic tool / Hybrid environment / Interface	Using VR for interior investigations
Design Development / Glare analysis			Studying glare conditions / Designing shading strategies	Diva / Revit Insight	Pedagogic tool	Using VR for glare and view real-time feedback
Design Development / Physical model development	Studying spatial characteristics / Developing details /Studying Materials	Physical modeling			Multi-sensorial / Deluge / Thinking space / Manual vs. Digital differences	Using AR or projector to superimpose information
Design Development / 3D model development - Interior	Studying spatial characteristics / Developing details /Studying Materials	Modelo + Google Cardboard / Unity			Dialogue / Real-time feedback	Using VR for interior investigations

The following sections provide a more coherent discussion of the sub-themes within each of the major themes of the framework.

7.3.1. Imagination Stimulation

The framework suggests that for qualitative studies, such as view study, the tools' role as a stimulus of imagination should be emphasized. It suggests several themes as possible avenues to achieve this goal.

One is *Thinking Space*, the ability of the design environment to create a space that supports design thinking. For instance, during the immersive case study, I have argued that the haptic interaction while making a physical model clears my mind and creates a space to focus on design thinking. As another example, I have argued that using a limited number of simple commands while working with SketchUp means that I master using them very quickly and their use becomes an unconscious task (procedural knowledge). As a result, my mind is clear for ideation and imaginative thinking while working on the 3D model. (4.14.1 Thinking Space and 5.12.1 Thinking Space)

Another theme is *Multi-sensorial*, the ability of the design environment to simultaneously stimulate various senses. For instance, during the immersive case study, I have argued that while working on the physical model, since I am closely working with materials (have a haptic interaction with the design), I have a better sense of the design's materiality. (4.6.2 Multi-sensorial and 5.4.1 Multi-sensorial) The multi-sensorial characteristic of the tool also contributes to the ability of the tool to foster design thinking, discussed in the previous paragraph.

Another avenue to stimulate the imagination is illustrated through the *Deluge* theme. It discusses the ability of the design environment to support the production of unintentional information that can help to stimulate the imagination. For instance, during the immersive case study, I have discussed how I decided to leave the cutting guidelines visible on some elements of the model after realizing they help with providing a sense of order inside the space. (4.7.2 Deluge and 5.5.2 Deluge)

Figure 7-5 Cutting guidelines on the wall piece as an example of unintentional information produced during physical modeling

Another theme is *Fuzzy vs. Precise* which suggests aiming for a correct balance between fuzziness and preciseness in representations based on the design stage. Several examples are discussed as part of the immersive case study. One is switching between various pencils and pens while drawing a sketch. I have suggested that this change of drawing tools and materials (each with its unique characteristics such as color or thickness) associates with layers of information. And in turn, these layers of information make the sketch more meaningful (containing more information) and more legible. Moreover, I have argued that this process of moving from fuzzy to precise through sketching, mirrors my thought process. Similar to my thought process, it starts with a fuzzy idea and moves toward a clearer and more precise version. Also, I have argued that it documents my iterations between the ideation and representation. Next, I have discussed the SketchUp styles feature as an example for implementing this theme in digital tools. However, I have pointed out that it is not as intuitive as a hand sketch and it remains a conscious act of representation. Therefore, this feature is most useful for communicating ideas with others and not as a replacement for the inner dialogue role of hand sketches. (4.15.1 Fuzzy versus Precise and 5.13.1 Fuzzy versus Precise)

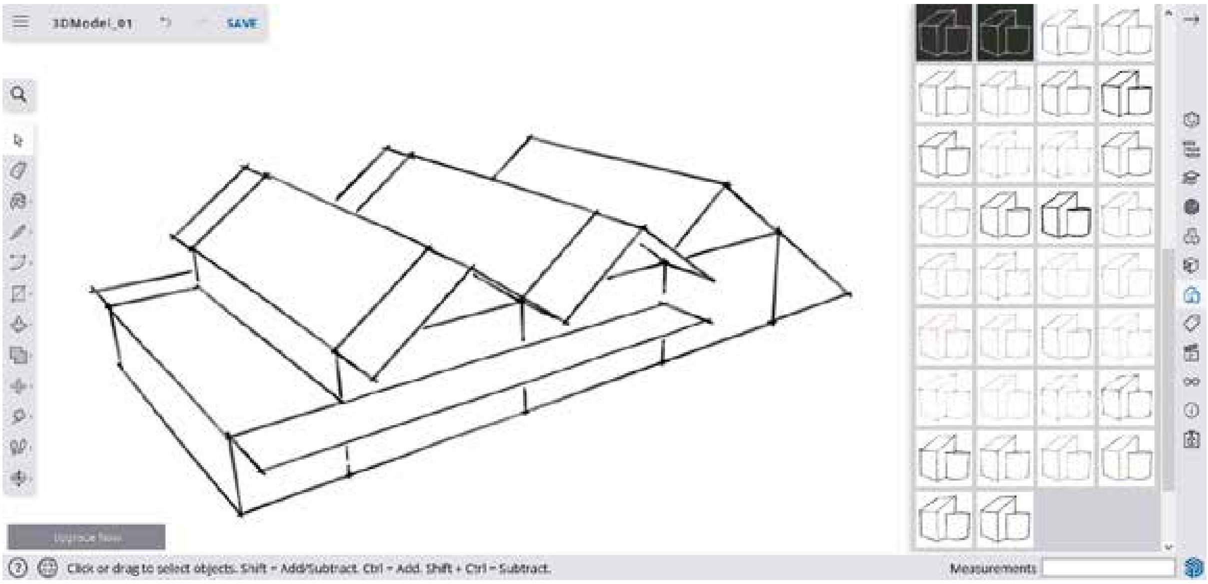


Figure 7-6 SketchUp styles feature as an example of fuzzy representation in digital tools

The correspondence of the tool to various stages of the design process can be discussed from other perspectives as well. The *Multiple Levels of Abstraction* theme discusses the ability of the design environment to simultaneously address multiple levels of abstraction from general concepts to small details. (5.14.1 Multiple Levels of Abstraction) As part of the immersive case study, I have suggested that BIM environments promote simultaneously handling different levels of abstraction. However, at least the implementation of this concept in tools such as Revit demonstrates two important flaws:

1. The inability of the current environments to foster design thinking and ideation. (see above)
2. The inability of the current environments to be incorporated at the early stages of the design process due to their complexity and rigidity.

From another perspective, the *Timing* theme discusses the ability of the design environment to provide/request the proper amount of information based on the design stage. (4.4.1 Timing and 5.10.1 Timing) For instance, the framework suggests that when developing a tool to support architectural decision-making, the developer should consider the following questions:

> When (during the design process) would the architect need the decision-support information that the tool can provide?
>
> What information should the architect know to be able to make related decisions?
>
> Does the architect have access to that information at the proper stage of the design process?

These different perspectives lead to another theme that addresses the correspondence of the tool to various stages of the design process. The *Evolving* theme discusses the ability of the interface to evolve and correspond to the demands and characteristics of different stages of the design process. (4.7.1 Evolving and 5.5.1 Evolving) For instance, during the immersive case study, I investigate eQuest and argue that the *evolving* feature in the interface of eQuest is the result of its developers' attention to the *timing* questions discussed above. In other words, the *evolving* feature of eQuest is the manifestation of the *timing* theme as a feature. (5.5.1 Evolving)

Figure 7-7 The three modes of eQuest, an example of an evolving interface

The framework also suggests considering the cognitive requirements of an imaginative process. For instance, the *Speed* theme promotes attention to speed limits inherent in the cognitive processes of the design. (4.5.2 Speed)

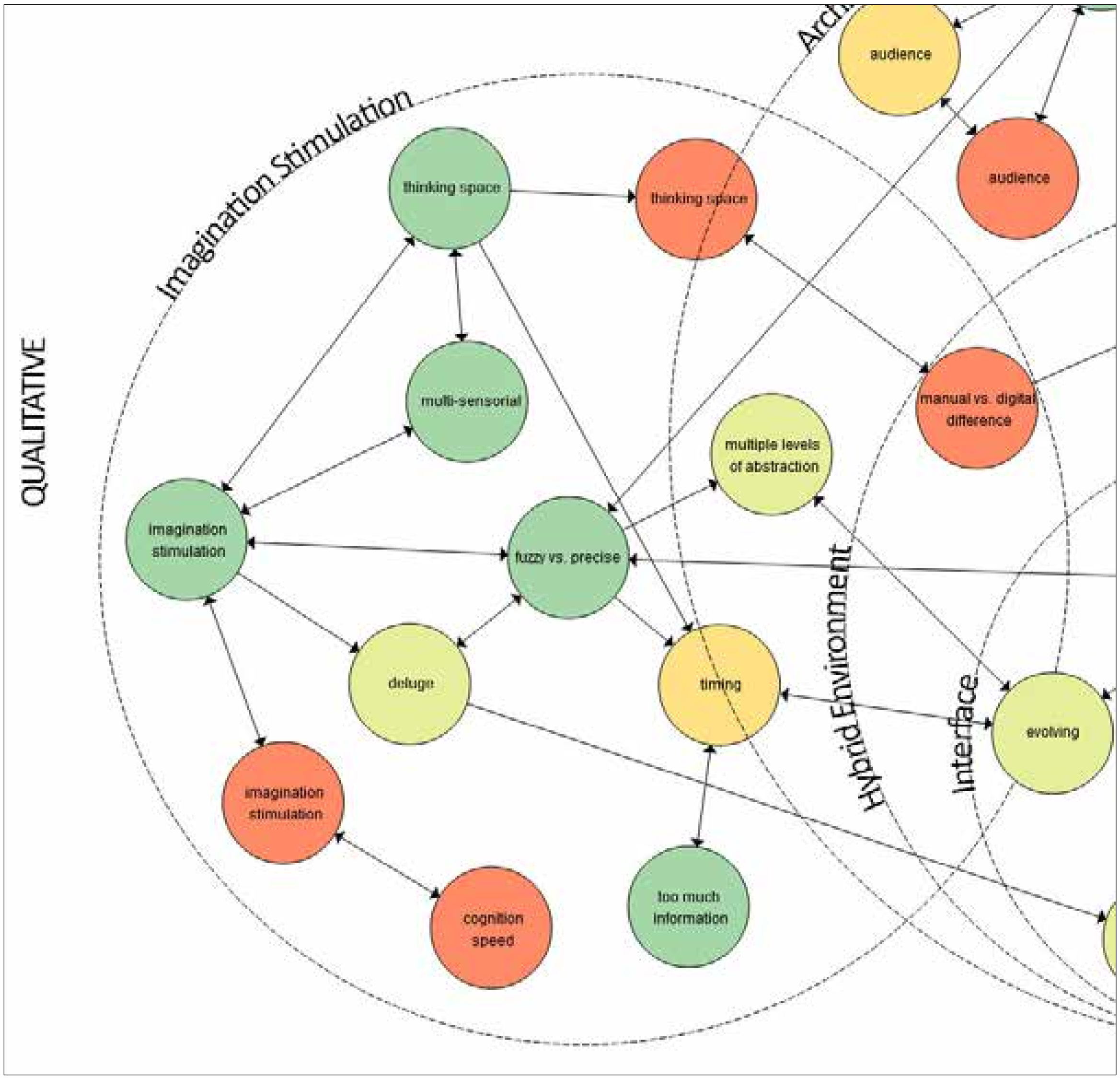


Figure 7-8 Imagination Stimulation sub-themes

7.3.2. Knowledge Acquisition

The framework suggests that for quantitative studies such as glare analysis, the architecture community needs to revisit the presence of digital tools in architecture schools' curricula. This can be done in two aspects: the process, and the content. From the process point of view, digital tools can be introduced early on while students are simultaneously learning design skills and techniques, where technique often includes the proper utilization of the tool. (4.22.1 Simultaneous Learning)

Regarding the content, there seem to be two areas to consider the incorporation of digital tools into the architecture schools' curricula:

1. providing the required *a priori* knowledge
2. fostering the ability to understand and validate the outputs of the tools used for quantitative studies

By providing the proper *a priori* knowledge regarding digital tools in schools' curricula, such as a basic understanding of scripting (4.9.2 Scripting and 5.7.1 Scripting), steep learning curves can be avoided in the future. However, this requires a closer relationship between tool developers and academia. Currently, the lack of proper *a priori* knowledge is more visible for quantitative studies such as glare analysis. (4.10.1 *A Priori* Knowledge and 5.8.1 *A Priori* Knowledge)

The other area is providing students with the necessary knowledge to understand and validate the outputs of digital tools that are used for quantitative studies. (4.8.1 Understanding and Validating Output and 5.6.1 Understanding and Validating Output) In other words, the students should be provided with the necessary knowledge to be able to:

1. Understand the analysis procedure (What is happening?)
2. Understanding the output (What is the analysis saying?)
3. Validate (Does it happen in real life? Can the results be believed?)

The framework suggests that during quantitative studies, oversimplification of the inputs and/or the process would impede the ability of the user to answer the above questions. While complex inputs and/or processes will increase the required *a priori* knowledge and make the learning curve steeper. Therefore, when selecting or developing a design support tool, finding the correct balance between simplifying and presenting the complexity is an important consideration. For instance, during the immersive case study, I argue that the oversimplification done by CoveTool limits the ability of the user to understand and validate the outputs. (5.6.1 Understanding and Validating Output)

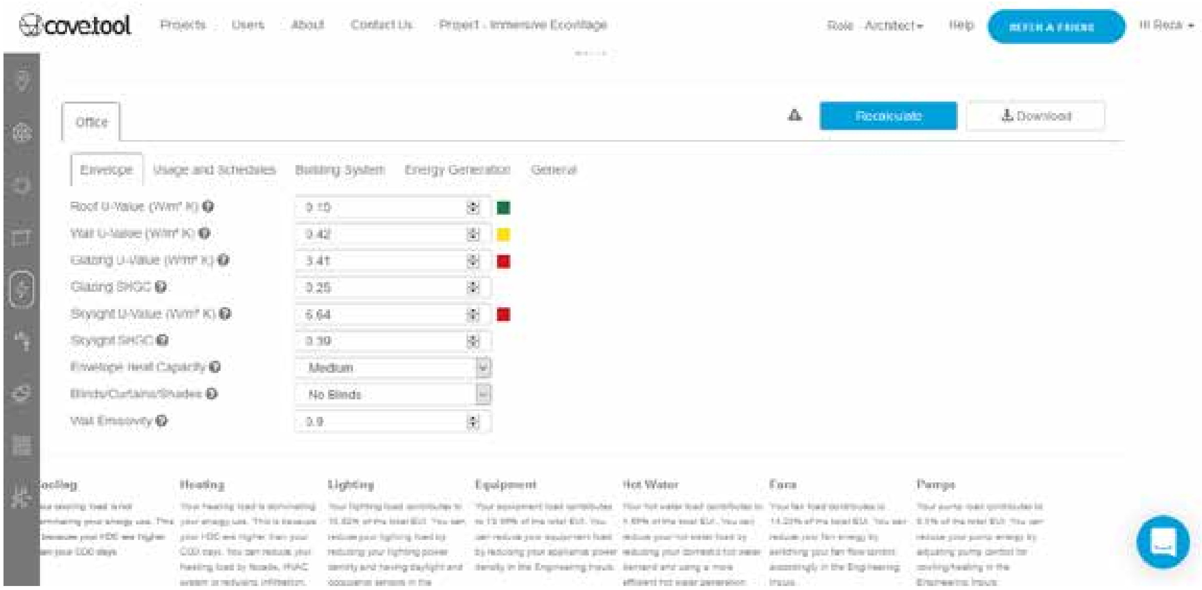


Figure 7-9 Example of input oversimplification (defining building envelope) in Covetool

However, the responsibility to provide this knowledge is not limited to architecture schools alone, and the tools themselves can play an important role. In instances that the user lacks required *a priori* knowledge and finds it necessary to go through a learning episode, tools can greatly simplify and expedite the learning episode by guiding the user toward the right resources. Such tools that provide access to a knowledge framework become *pedagogic tools*. (4.24.1 Pedagogic Tool and 5.20.1 Pedagogic Tool)

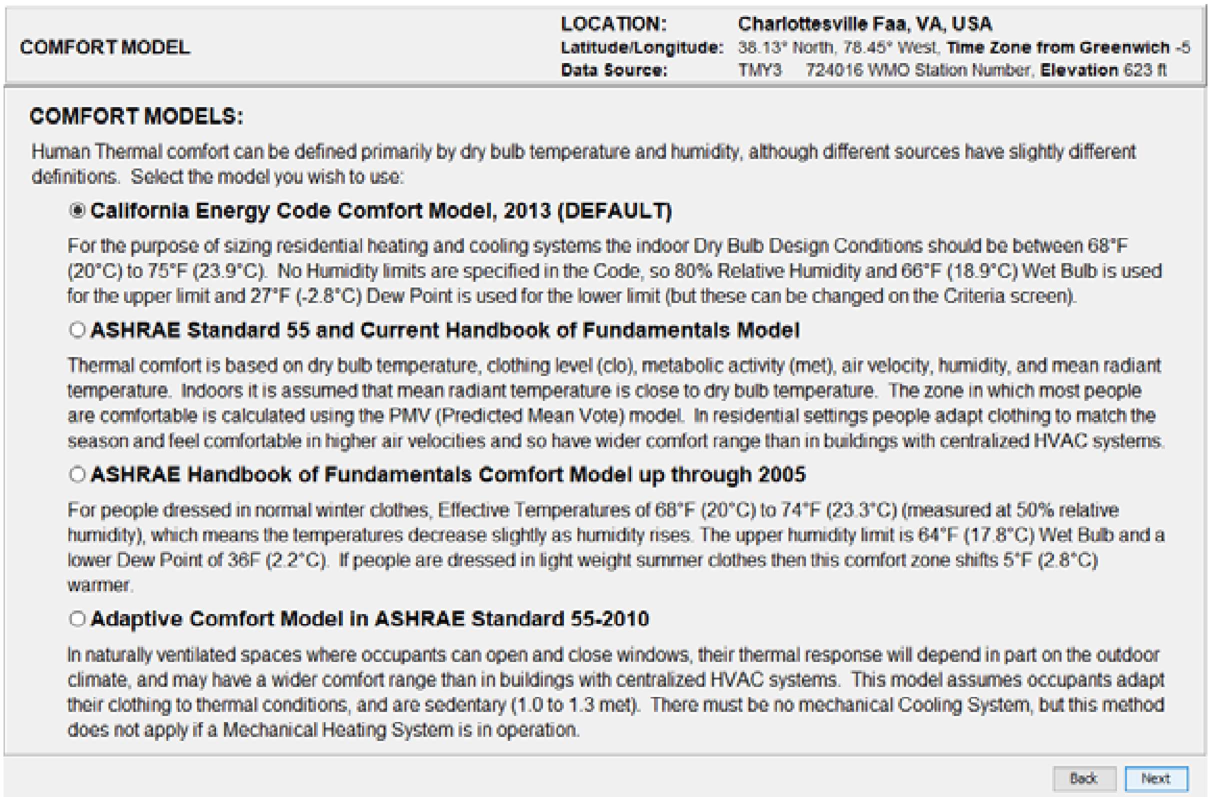


Figure 7-10 Climate Consultant comfort model selection wizard, an example of a pedagogic tool

Parametric capabilities (4.21.1 Parametric), as well as real-time feedback (4.16.1 Real-time Feedback and 5.16.1 Real-time Feedback), are important features supporting this pedagogic process. Also, the pedagogic characteristic of a tool is dependent on its ability to create a mental link between an experiment and the *a priori* knowledge that the architect has acquired in his/her education. For instance, during the immersive case study, I have discussed Diva for Grasshopper as a daylighting tool that incorporates all these three features. (5.20.1 Pedagogic Tool)

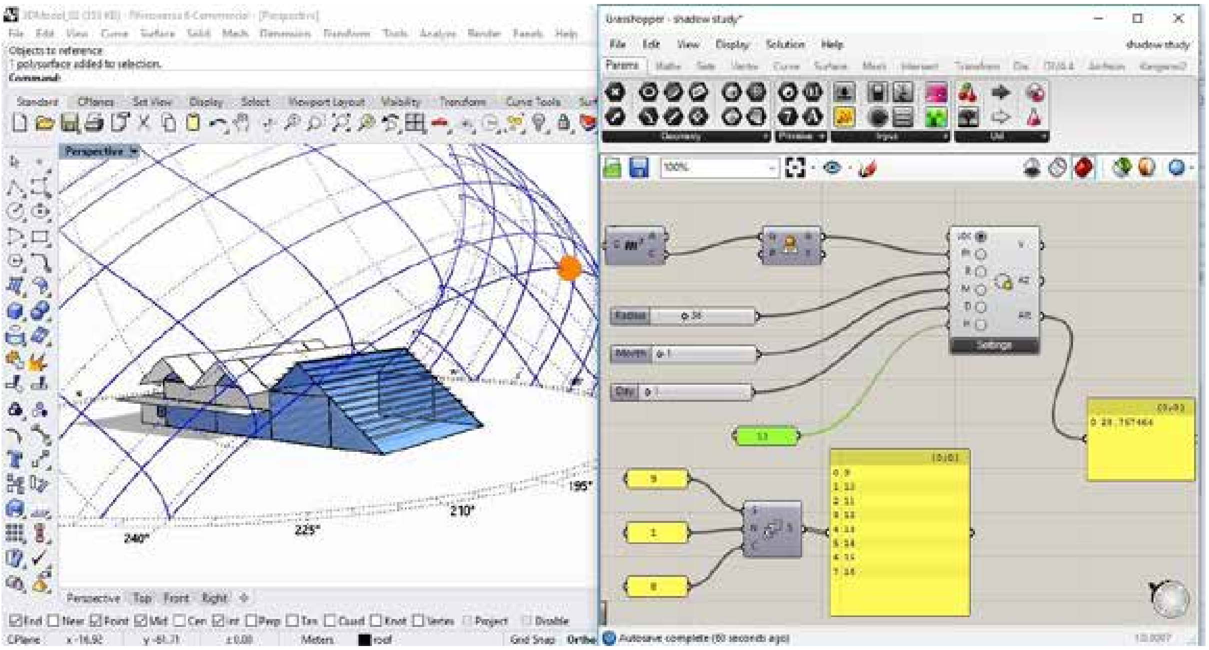
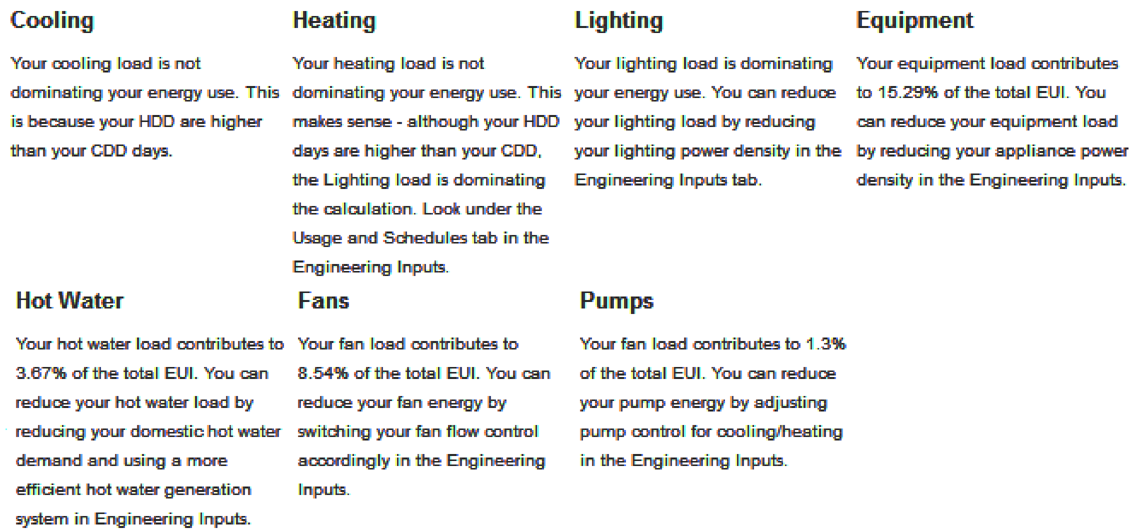


Figure 7-11 A screenshot from Diva representing its parametric capabilities, real-time feedback feature, and the usage of the sun-path diagram

Furthermore, the framework points out that to be educational, tools should present *processed information* rather than *raw data* to their user. In other words, the raw data produced as the output of a quantitative analysis should be presented to the user with an overlay of explanatory information. (5.20.1 Pedagogic Tool) For instance, the report section in CoveTool provides an explanation of the results. This feature helps users with less experience to have a deeper understanding of the analysis results.



Cooling

Your cooling load is not dominating your energy use. This is because your HDD are higher than your CDD days.

Heating

Your heating load is not dominating your energy use. This makes sense - although your HDD days are higher than your CDD, the Lighting load is dominating the calculation. Look under the Usage and Schedules tab in the Engineering Inputs.

Lighting

Your lighting load is dominating your energy use. You can reduce your lighting load by reducing your lighting power density in the Engineering Inputs tab.

Equipment

Your equipment load contributes to 15.29% of the total EUI. You can reduce your equipment load by reducing your appliance power density in the Engineering Inputs.

Hot Water

Your hot water load contributes to 3.67% of the total EUI. You can reduce your hot water load by reducing your domestic hot water demand and using a more efficient hot water generation system in Engineering Inputs.

Fans

Your fan load contributes to 8.54% of the total EUI. You can reduce your fan energy by switching your fan flow control accordingly in the Engineering Inputs.

Pumps

Your fan load contributes to 1.3% of the total EUI. You can reduce your pump energy by adjusting pump control for cooling/heating in the Engineering Inputs.

Figure 7-12 Covetool report, an example of an overlay of explanatory information

Online databases are an important example of pedagogic tools. (4.11.1 Online Databases and 5.9.1 Online Databases) Such databases can perform as a decision-support framework, a bundled set of information that helps the architect as a reference to frame the design question. (4.10.2 Frameworks and 5.8.2 Frameworks) For instance, Climate Consultant refers the user to other resources such as the online 2030 Palette database, for further reading. Consequently, the tool provides a map that guides the users while allowing them to decide how deep they want to go for each guideline.

Figure 7-13 Climate Consultant directing the user to 2030 Palette

However, when developing these knowledge frameworks, an important aspect is the interface. In other words, how the information enclosed in the framework would be presented to the architect. (4.25.1 Interface and 5.21.1 Interface) For instance, during the immersive case study, I have discussed that the wizard interface (a sequence of screens in order, with inputs from earlier screens determining the screens that would follow), in tools such as Climate Consultant and eQuest, is very appropriate for the simple and sequential process that these tools follow. (5.21.1 Interface)

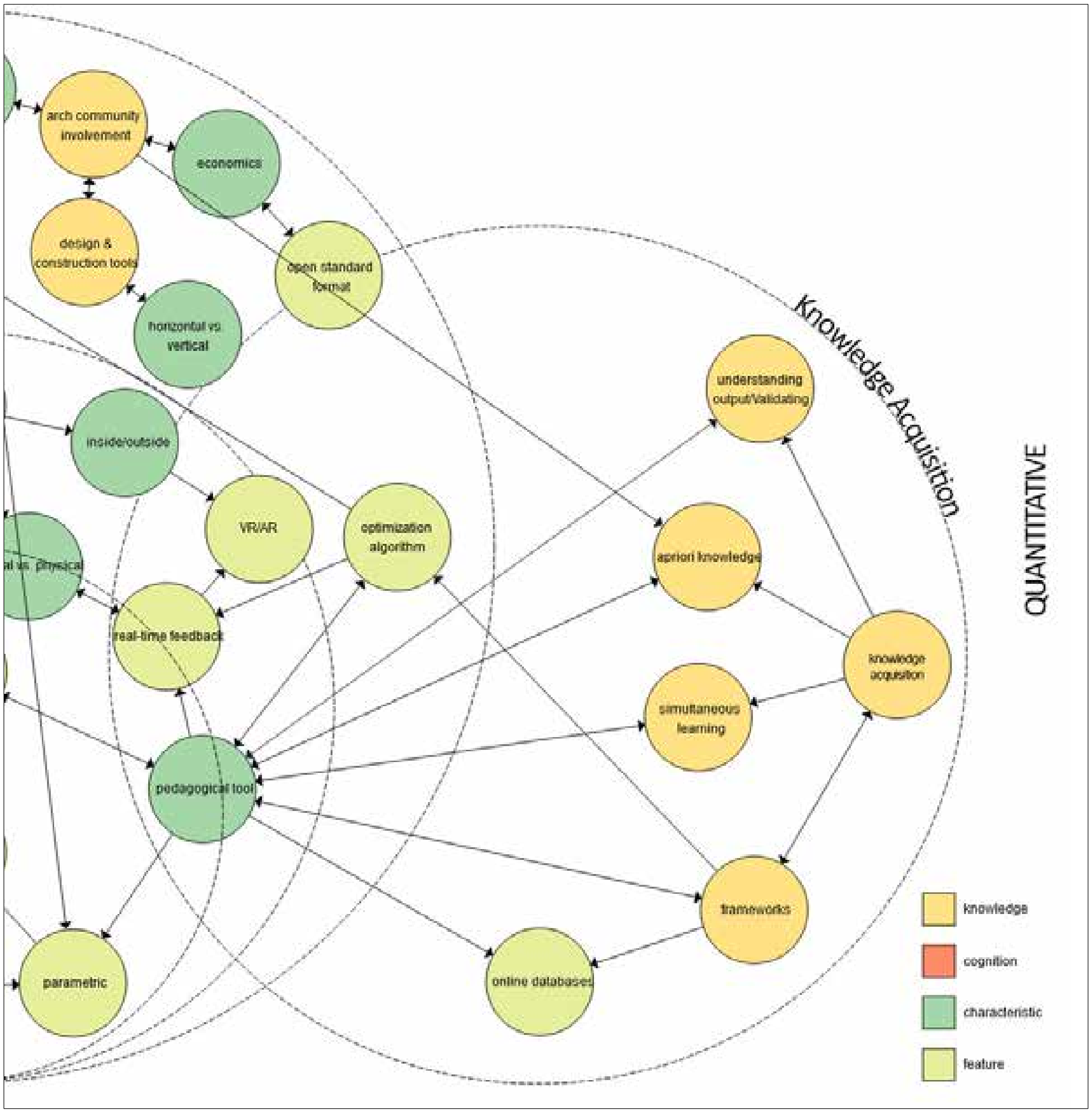


Figure 7-14 Knowledge Acquisition sub-themes

7.3.3. Architect as Toolmaker and Design Environment Coordinator

The framework suggests that to bridge the gap between qualitative and quantitative studies during the design process, the role of the architect as toolmaker and design environment coordinator should be emphasized. The concept of the architect as toolmaker does not necessarily mean that the architect or the architecture community would be developing tools such as computer software, but rather it means that the architect should be the person who connects various tools together and creates a unique constellation of tools to define the design problem.

This approach reinforces the *architect's control* over the design process. For instance, during the immersive case study, I have pointed out that the reports produced by CoveTool include information (such as results of a glare analysis) that I did not provide any input for. I argue that this lack of control makes the user question the validity of the results. (4.13.2 Architect's Control and 5.11.2 Architect's Control)

The concept of the architect as toolmaker also supports dialogue during the design process by enabling the architect to bring and connect various perspectives into the design environment. The *dialogue* theme has two aspects that this approach supports both:

1. internal dialogue (architect with him/herself). Sketching is an example of a tool supporting this aspect. (4.19.1 Dialogue)
2. external dialogue (communication with various audiences and parties involved in the design project). 3D commenting feature in Modelo (5.15.1 Dialogue) or role selection feature in CoveTool (5.17.1 Audience) are examples of attention to this aspect.

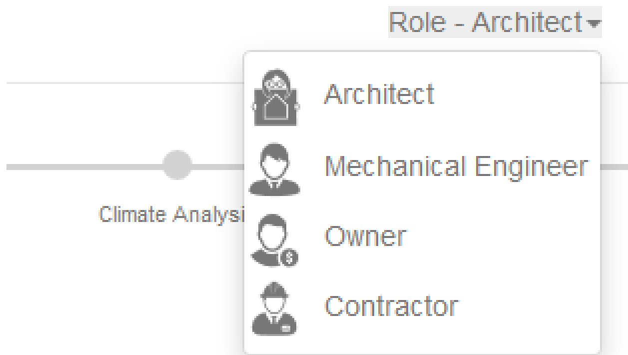


Figure 7-15 Covetool role selection feature

Most importantly, the realization of this concept requires *architecture community involvement* to:

1. Provide their intuitive knowledge about design and construction. ArchDaily and Climate Consultant (both with architects in their development teams) are examples that demonstrate how this involvement translates into features and characteristics that are tailored for architects and their workflow. (5.18.1 Architecture Community Involvement)
2. Balance the power dynamic which exists in current economic models. The framework suggests that the architecture community (academics in specific) can advocate for open and standard file formats to facilitate interoperability between various digital platforms (including 3D modeling programs) and to support the iteration process during the design development stage. (5.7.2 Open Standard Formats)

The interface has an important role in the implementation of the Architect as Toolmaker and Design Environment Coordinator concept. *Parametric* capabilities, provided through *scripting*, support this process. Visual scripting environments such as Grasshopper are a platform to connect various components of the design environment. These environments support the iteration stage by clearly presenting the flow of the information. (5.7.1 Scripting)

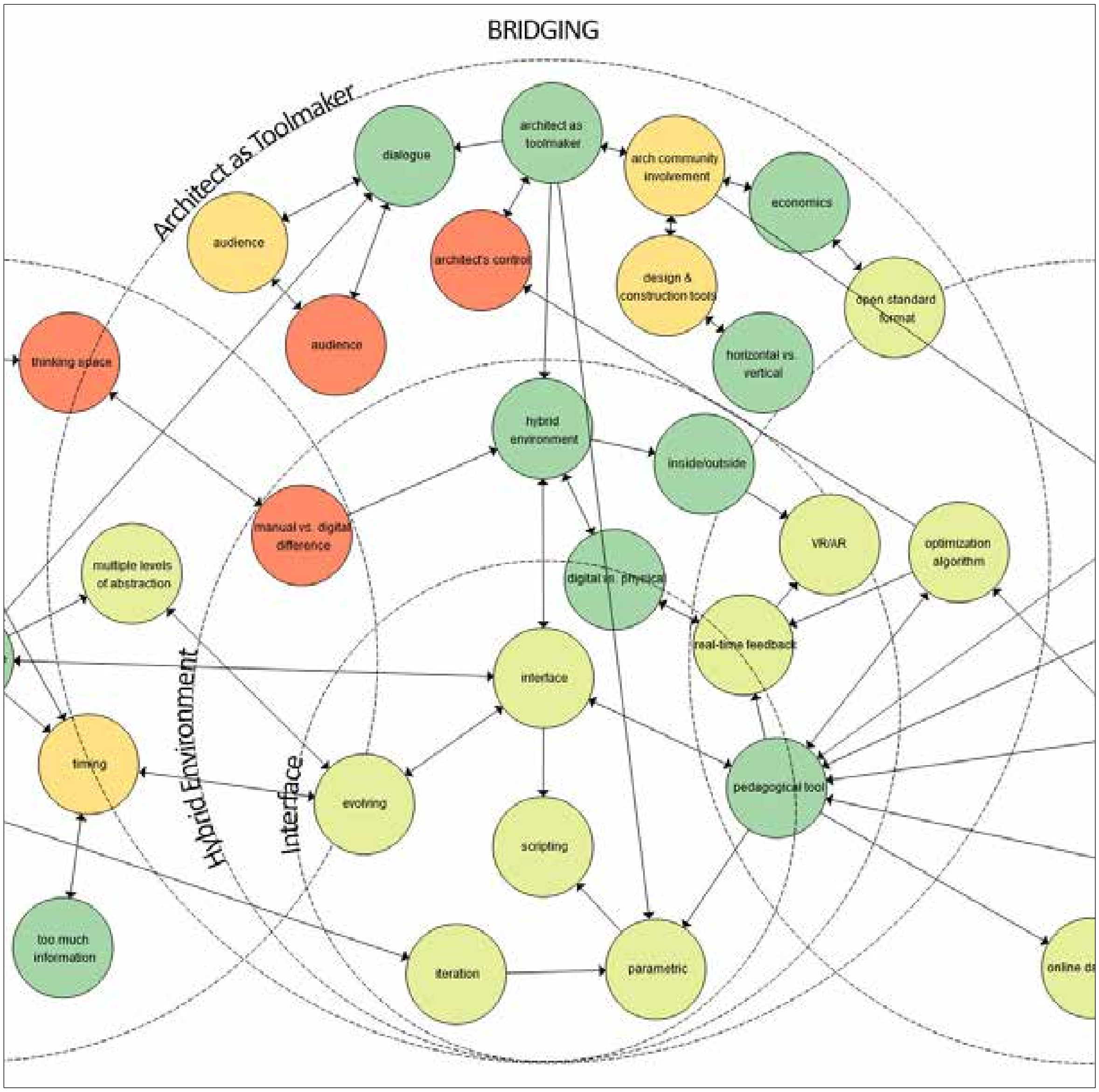


Figure 7-16 Architect as Toolmaker and Design Environment Coordinator and Hybrid Environment sub-themes

7.3.4. Hybrid Environment

Central to the *Architect as Toolmaker and Design Environment Coordinator* theme is the concept of *Hybrid Environment*. (4.24.2 Hybrid Environment and 5.20.2 Hybrid Environment)

The concept of hybrid design environments is to question dualities such as digital versus manual tools and to advocate for a design environment that simultaneously supports:

Manual and digital tools (4.23.1 Manual versus Digital Differences and 5.19.1 Manual versus Digital Differences). For instance, I have investigated how hand-sketching inside digital 2D drafting and 3D modeling environments can support design thinking. (5.20.2 Hybrid Environment)

Physical and virtual representations (4.24.3 Relationship between Digital and Physical Environments). For instance, I have discussed how physical models can be more supportive of design thinking at the early stages of the design process, compared to digital 3D models. (5.19.1 Manual versus Digital Differences)

Inside and outside (immersive and non-immersive) studies (4.18.1 Inside/Outside) For instance, immersive and non-immersive digital environments are more supportive of a qualitative study of the interior and exterior spaces, respectively. (5.16.1 Real-time Feedback)

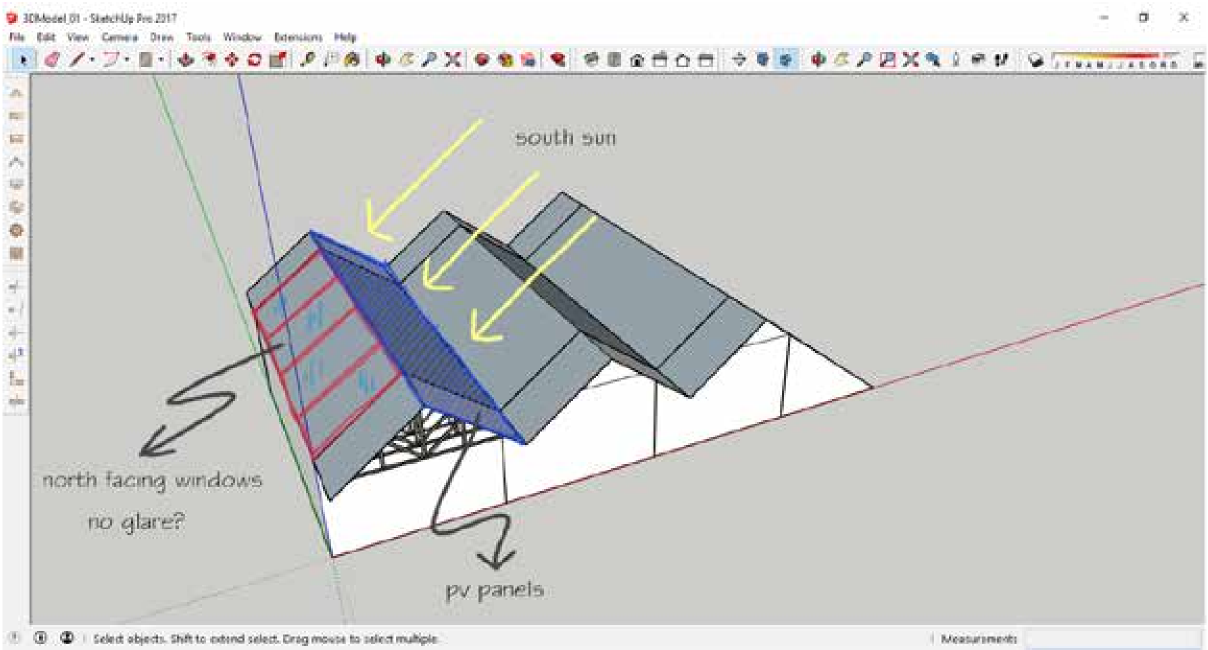


Figure 7-17 A mockup version for hand sketching capabilities inside SketchUp

A key goal of a hybrid design environment is to provide *real-time feedback* for both qualitative and quantitative studies. (4.16.1 Real-time Feedback and 5.16.1 Real-time Feedback) I have discussed current developments in providing real-time feedback for separately studying view and daylighting during the immersive case study. (5.16.1 Real-time Feedback) Merging these two areas of development is essential to develop tools that support simultaneously addressing qualitative and quantitative criteria such as view and glare. An important area of development for supporting such real-time feedback is the application of *Virtual Reality (VR) and Augmented Reality (AR)* tools. For instance, I have discussed Modelo, an online VR service that utilizes Google Cardboard as the hardware. It simplifies the 3D model to the VR presentation conversion process. However, I point out that services such as this need to be better integrated into the 3D modeling environments, to enable the architect to switch back and forth between designing, modeling, and reviewing their model in VR. (5.16.1 Real-time Feedback)

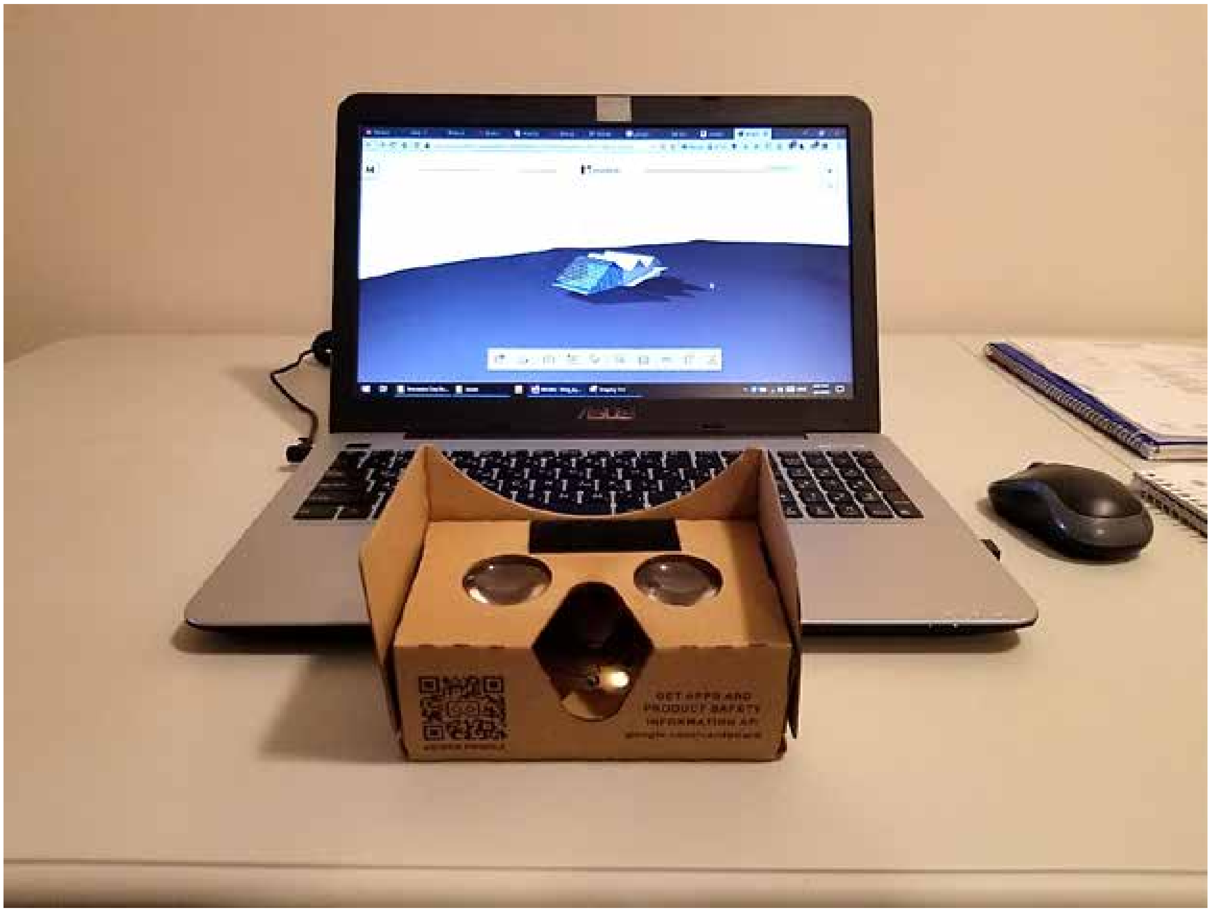


Figure 7-18 Using Modelo and Google Cardboard to incorporate VR for interior studies

7.4. Recommendations for Architects

The following infographic (Figure 7-19) provides recommendations based on this research findings and conclusions (refer to Table 7-1) for architects in practice and architecture students. These recommendations are meant to be simple and practical, so the architects would be able to understand them without reading the whole document.

This infographic focuses on various strategies to simultaneously address qualitative and quantitative criteria. The recommendations are arranged in a matrix format. The horizontal axis of the matrix defines the study area: qualitative study strategies on the left, quantitative study strategies on the right, and the synthesis of qualitative and quantitative approaches on the center. The vertical axis of the matrix defines the design process stage or the complexity of the design process. Therefore, recommendations on the lower part of the matrix are meant for later stages of the design process or projects with higher complexity.

Moreover, these recommendations provide examples for the themes that were discussed in the previous sections, especially the *Hybrid Environment* and *Architect as Toolmaker and Design Environment Coordinator* themes. These recommendations put the architect in the role of the design environment coordinator. The architect connects various tools to one another and creates a hybrid design environment that includes manual and digital tools, immersive and non-immersive environments as well as physical and virtual ways of representation.

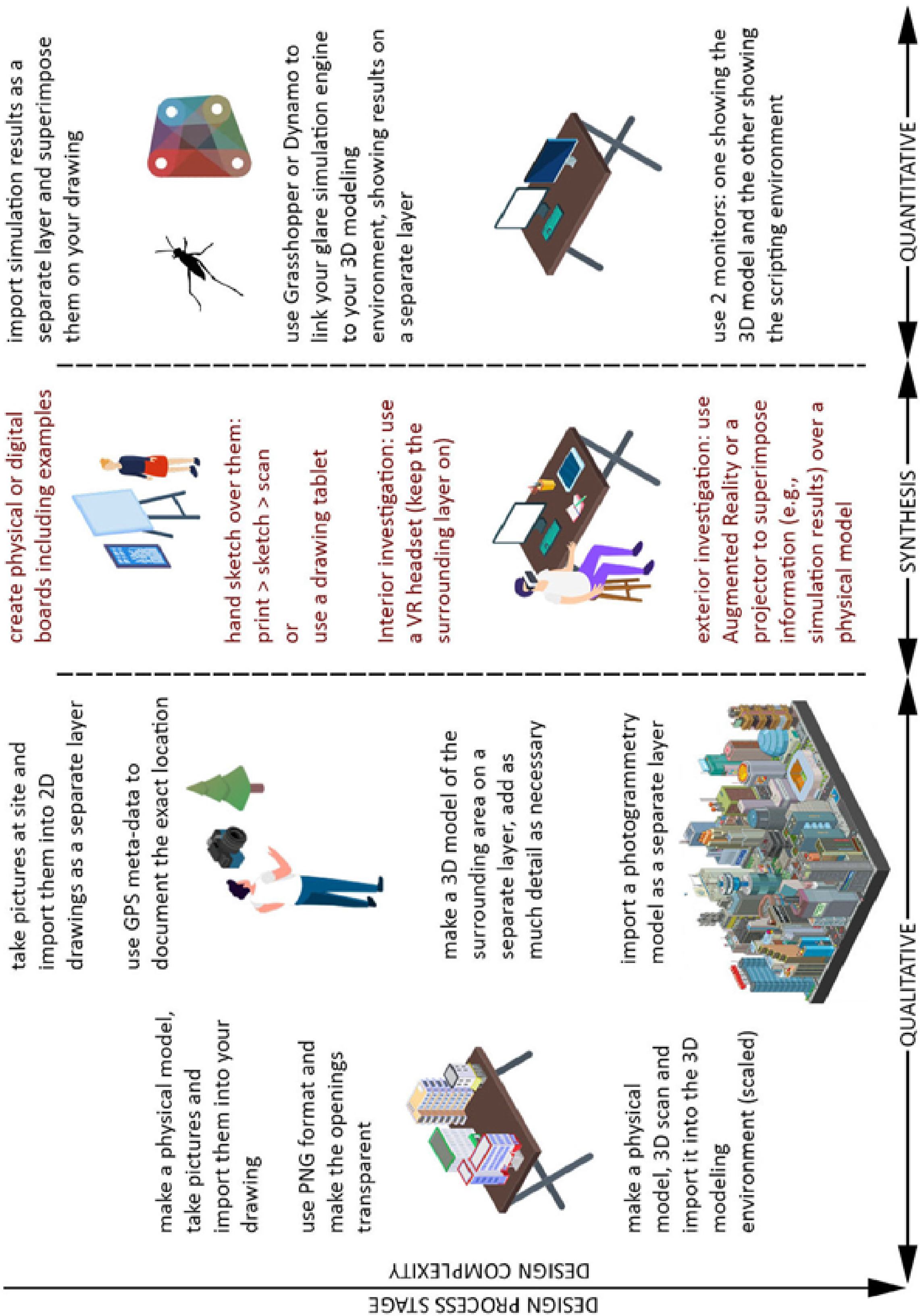


Figure 7-19 Recommendations for the architects

7.5. Contributions to the Body of Knowledge

This research addresses a gap in the literature that is illustrated in Figure 7-20. This diagram represents three major areas in architectural research (the study of the design process, design computation, and representation history/theory). It also represents the major sources that have been referenced in this research and their location within these major areas of research.

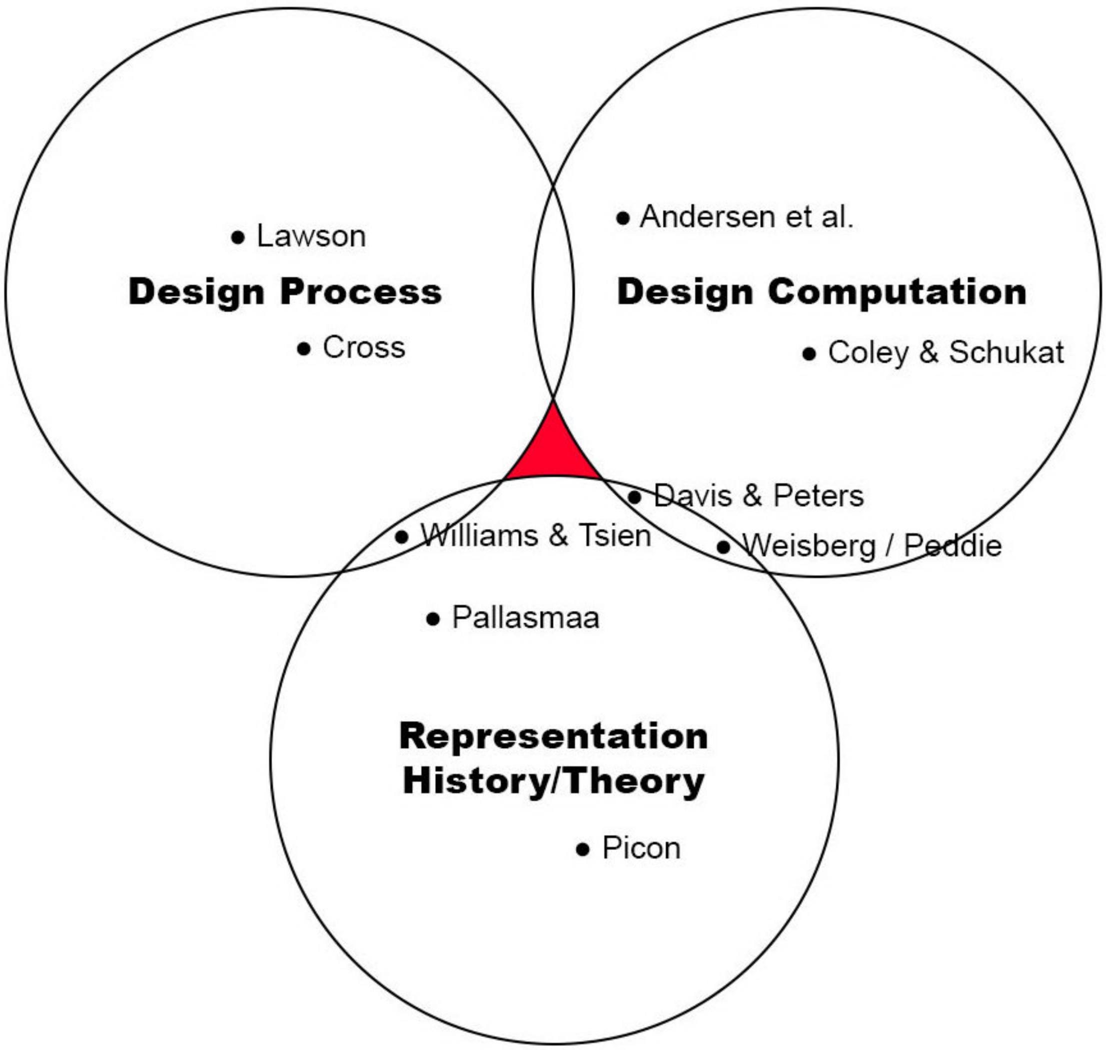


Figure 7-20 Mapping the gap in the literature

The framework, in its final form, provides a map of the areas and the themes that need consideration when developing an architectural tool that is expected to simultaneously address qualitative and quantitative criteria at the early stages of the design process. It also provides a roadmap for future research on the subject.

For practicing architects, the framework provides guidance to choose proper tools and form their design environment. In specific, Chapter 5, includes many examples from the immersive case study step.

Also, this research provides a new model of communication between the architecture community and the software developers. In this new model, the architecture community adopts a more active role and provides the software developers with features and characteristics of the tools they need. The methodology of this research is an example of how these features and characteristics can be specified through an iterative process that engages the stakeholders.

From the methodological point of view, this research illustrates that traditional journal writing as a qualitative research technique needs to be expanded to incorporate new mediums such as images and videos along with text and hand-drawn sketches. I accomplished this task in this research by storing and organizing the image and video files in a folder on my computer and referencing them in my handwritten journal. In one instance, I printed out an image and attached it to the journal. In the future, a digital journal-keeping environment that enables the researcher to combine images and videos with writings and sketches from a drawing tablet might facilitate this process.

7.6. Study Limitations and Future Research

As a PhD level research with limited funding, I was able to conduct a limited number of interviews. The effect of this limitation was moderated using the Delphi method. However, further interviews in the future can help to polish the framework. In specific, although many efforts were made to have some of the software developers as participants during the interviews and the Delphi panel, these efforts remained unsuccessful. Moving forward, participation by the software developing community can improve the framework.

The immersive case study method was appropriate for the scope of this research. However, a comparative case study in the future can help to increase the credibility of the findings and conclusions by reducing personal biases and inclinations. For now, this limitation was addressed by:

1. illustrating the connections between the findings from the immersive case study stage and the findings from the literature review and the interviews
2. member checks through the Delphi method

Moreover, the framework creates a general map of the important areas to be considered for simultaneously addressing qualitative and quantitative criteria during the early stages of the design process. Future studies focusing on certain themes that were introduced in this research can expand the framework and provide further details.

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Appendix A

The following is the interview guide that I used during the interviews. Based on the conversation, I might have changed the order of the questions or skipped/added new ones. (refer to 3.3.2 Interviews)

1. Can you please tell me a little bit about your background? What programs have you studied in? And, where? Where have you worked previously? Where are you working now?
2. What steps you usually go through during a design (class) project?
    a. At what stage of the design process do daylighting and view affect your decision-making? Please explain how you think that these issues affect your decision-making.
3. What tools you usually use? (What tools you require/recommend to your students?)
4. How do you study the view in your designs (class projects)? Do you have a specific project you want to describe as an example?
    a. Do you think that your assessment process limits your design thinking in any way? Please explain.
    b. If you could alter your process in any way what would they be?
5. Have you ever studied glared during a design (class) project? How do you study the glare in your designs (class projects)? Do you have a specific project you want to describe as an example?
    a. What tools do you use to assess glare performance? Why those tools (what features do they have that support the process)?

b. Does the use of those tools influence your design process? If so how?

c. Do you think that the use of these tools limits your design thinking? If so how?

d. Do you think that the use of these tools limits your design process (interoperability for example)? If so how?

e. What suggestions would you have as modifications or new features for a glare performance assessment tool? As related to input, user interface, interoperability, and output interpretation?

f. If you could alter your process in any way what would they be?

6. What background preparation and fundamental knowledge have you acquired to prepare yourself for addressing glare and view?

7. What are your goals in addressing glare and view? To inform your design, to show to colleagues for comment and suggestion, to show to a client to support your proposition, etc. Do your processes and tools change to meet these different goals? If so how?

8. Do you have a specific successful or unsuccessful example from your previous projects (classes) of trying to simultaneously address qualitative and quantitative criteria, like view and glare?

    a. When conflicts arise between the quantitative (performance) and qualitative aspects of the design how do you resolve the conflicts?

    b. Do you think that your glare and view assessment processes provide enough information for effective decision-making? If not what modifications would you suggest?

9. What do you think about the influence of digital tools on architectural design?

10. Imagine your ideal design environment, how does it look like?