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TITLE:

# Thermal Cubic:
# Virtual Reality Based Thermal Data Visualization Engine for the Early Stage of Compact Residential Design

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# Abstract

Nowadays, thermal comfort has become an important concern in the building industry due to its great impact on the living environment especially in compact urban space. This thesis research proposes a prototyping system to combine emerging Virtual Reality (VR) technologies with modeling and thermal analysis tools to provide dynamic and immersive thermal analysis and visualization experience inside the virtual environment to enable better design iteration process during the early stage of urban residential design and to raise professional attention towards the importance of evaluating thermal comfort during the initial stage of a design project.



# Keywords

Thermal Analysis; Thermal Comfort; Virtual Reality; Virtual Experience; Data Process; Data Visualization; Modelling; Computational Design

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# 1 Introduction

This research has an intention of emphasizing the significance of the consideration of thermal and physical comfort in early stage of urban residential design. It explores the potential of Virtual Reality as an approach to providing immersive and interactive visualization of thermal data and measures its effectiveness for early stage of compact residential design.

"Well building hath three conditions: firmitas, utilitas, and venustas"

De architectura, Marcus Vitruvius Pollio (Rowland et al., 2001)

There are numerous definition of "what is a successful architectural design" existing in the world, with the above one from around B.C. 15 which might be the most famous. Vitruvius addressed the importance of firmness(firmitas), commodity(utilitas), and delight(venustas). Among these three key factors, firmness or physical strength of the building's integral structure can be ensured with much less effort nowadays with the development of structural engineering, civil construction and material technology. The details of this factor has already been taken care of by engineers participating in the building projects. Commodity summarises the functional requirements of arrangement of spaces and systems from the residents. And delight is related with style, proportion, and aesthetics. commodity and delight remain two key factors for architects to devote their effort to create extraordinary buildings while the mechanical system part of commodity is more objective, on the other hand, delight is more personal and private to the occupants' preference.

In the aspect of modern architecture, outstanding examples have been provided which satisfy the firmness, delight according to the users' imagination, the part of "functional requirements of space" of commodity, and even became masterpieces of modern architecture. However, there were severe complaints from owners saying that the buildings had flaws in the system part of commodity. For example, "The matron of the famed Villa Savoye, Mme Savoye, wrote several letters to Le Corbusier to complain that there was leaks in the

garage and bedrooms during an inclement weather, 'it is still raining in our garage', and the rainfall on the skylight made a terrible noise preventing them from sleeping" (Sully, 2009), when Farnsworth moved in the noble house designed by Ludwig Mies van der Rohe in December 1950, the roof leaked badly and "the heating produced a film that collected on the inside of the windows with the systems gathered together in one inaccessible stack" (van der Rohe et al., 2014).



***Figure 1.1:*** *Floodwaters at the Farnsworth House in 2008, via modernhousenotes.blogspot.com*

It is ironic that in order to pursue a modern, fluid space and a broad view with flat roof, large glass window, and column structure, modern architecture sacrifices the occupants' modern living experience and pushes them back to rural and ancient situations where there was barely no thermal or mechanical systems such as insulation, fresh air and air-conditioning, and drainage.

In such context, it is necessary to draw attention of architects and architectural designers to evaluate the thermal and physical effectiveness or at least consider these aspects during the design process at a relatively early stage. With assistance of the rapid development and

iteration of design media, modeling tools, and evaluation approaches, there are countless tools that can be introduced to enhance the evaluation of commodity.

This research chooses thermal comfort among those factors of commodity and explores a pipeline of gathering, analysing thermal data, mapping data and space within Rhinoceros3D and Grasshopper, creating dynamic visualization using Processing, Adobe After Effects, and achieving interactive and immersive experience through Virtual Reality. Tests and survey are carried out to evaluate the proposed approach and are documented and discussed in detail in the following method and discussion chapters.

This project aims to make contributions to current architectural design education and industry in three aspects. First, it prototypes a potential way of utilizing Virtual Reality, modeling and computational tools to visualize related thermal data. Second, it provides a pipeline and experience for professionals to evaluate the thermal effects of their design and do iterations accordingly. And Finally, it emphasizes the significance of the consideration of thermal and physical comfort at early stage of residential design which might benefit further design process and elicit future researches on the topic.

# 2 Background

In this chapter, the situation related to the thesis research which has a foremost focus on the application of Virtual Reality working with architectural modelling tools as a thermal data visualizer in architectural design area is discussed with an overview of technology and existing tools.

## 2.1 Situation

This section describes current situation regarding the participatory of thermal performance in architectural design and built environment industry and the utilization of data visualization and virtual reality in related fields.

### 2.1.1 Thermal Performance in Built Environment

With the rapid development of economics and technology, there is an increasing focus on living comfort of built environment nowadays when people are choosing residence. As a key factor of living comfort, the impact of thermal environment which includes temperature, insulation, humidity, air flow and so on, has been gradually emphasized. Supported by building energy simulation researchers earlier in this century, "Calculation of the indoor comfort temperature, being the most important environmental parameter of a residential building, ..." (Peeters et al., 2009). Due to the advancement of related theory, thermal performance is defined as the heat transfer performance, which is the measurement of the thermal exchange process between different systems including conduction, convection, radiation and phase change. Except for personal factors like clothing and wellbeing, thermal environment has a concentration on air and radiant temperature, air velocity, surface water and humidity.

Especially in urban residential buildings, where both exterior and interior space are relatively compact, the choices of consumers, tenants and investors in real estate industry are showing a tendency of focus on thermal comfort related performance. "The building industry nowadays is facing two major challenges - the increased concern for energy reduction and the growing need for comfort improvements." (Vesely and Zeiler, 2014). Energy consumption is another concern due to the increasing observations and researches on climate change that shows the abuse of fossil fuels, chemical artifacts and water resources are resulting in global warming, extreme weather, and food shortage. So it seems like enhancing thermal comfort and lowering energy consumption are contradictory aspects of urban living while compromised solutions can be put up through paying attentions to thermal performance by participants among the whole life cycle of the buildings .

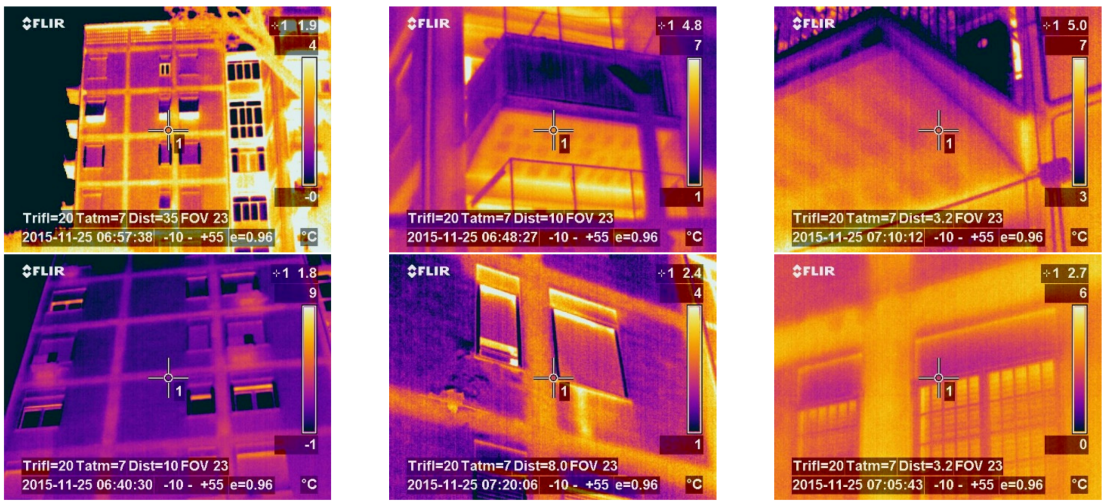



***Figure 2.1:*** *Thermal Analysis and Energy-Efficient Solutions. (Mortarotti et al., 2017)*

It is easy to imagine that, among concrete jungles of metropolitan area, buildings with different functionalities are strictly next to each other. The relations of these buildings are subtle owing to the vague between dependency, reflection, and occlusion. In such circumstances, residents tend to restrict most of their activities inside the dwelling and have barely no interaction with other residents, which makes living comfort even more important for such a living pattern. However, as articulated through a case study of thermal

comfort in compact urban environments, "this compact morphology, however, obstructs the breezes that are an essential component to achieve thermal comfort by passive means in warm and humid climates. New courtyard buildings should be designed in such a way that natural ventilation and thermal comfort are enhanced. Research on natural ventilation and thermal comfort in compact urban environments, however, is scarce." (Tablada et al., 2009). Thermal environment and living comfort related research is way off from adequate which is an additional reason for complaints of urban residents. Although utilization of mechanical systems such as air-conditioning and humidifier can address the effects of relatively low thermal performance of residential buildings, energy efficiency is unsatisfactory in this case and some residence also reflect that the thermal comfort achieved by these mechanical systems is not as good as natural ventilation. Researches on urban chronic of residents also indicates that natural environment is more beneficial to human beings than thermal environment simulated through mechanical systems which might produce toxic gas or poison and cause diseases of residents.

### 2.1.2 Thermal Performance Participatory in Architectural Design

Currently, thermal performance is introduced to the building evaluation system commonly in a later stage of design with consideration of material, insulation and construction details. The potential of better thermal performance and energy efficiency might be able to be achieved if engaging thermal performance at an earlier stage of design. Such a point is supported by researchers from Stanford University, "Decisions made during a building's early design stages critically determine its environmental impact. However, designers are faces with many decisions during these stages... As a result, designers often defer decisions to later stages of the design process." (Basbagill et al., 2013). If there is no special requirements put forward by management party, designers will usually run some basic thermal performance test based on the design model with some fixed parameters such as the specifically chosen day with the best radiance to show the diagram in the presentation slides.

These results are likely to deviate from the real daily thermal effects of the building due to the inaccuracy of models, calculation tools and the input parameters. In addition, the 2D diagram in the slides is fixed with some chose dates, which is difficult to show the gradual change of thermal effects and living comfort accordingly. As a result, the contempt of thermal effects becomes a consensus and during the presentation the client of the property as well pays fewer attention to this topic than to design, structure, or material that might attract more residents for the property when the project is finished.

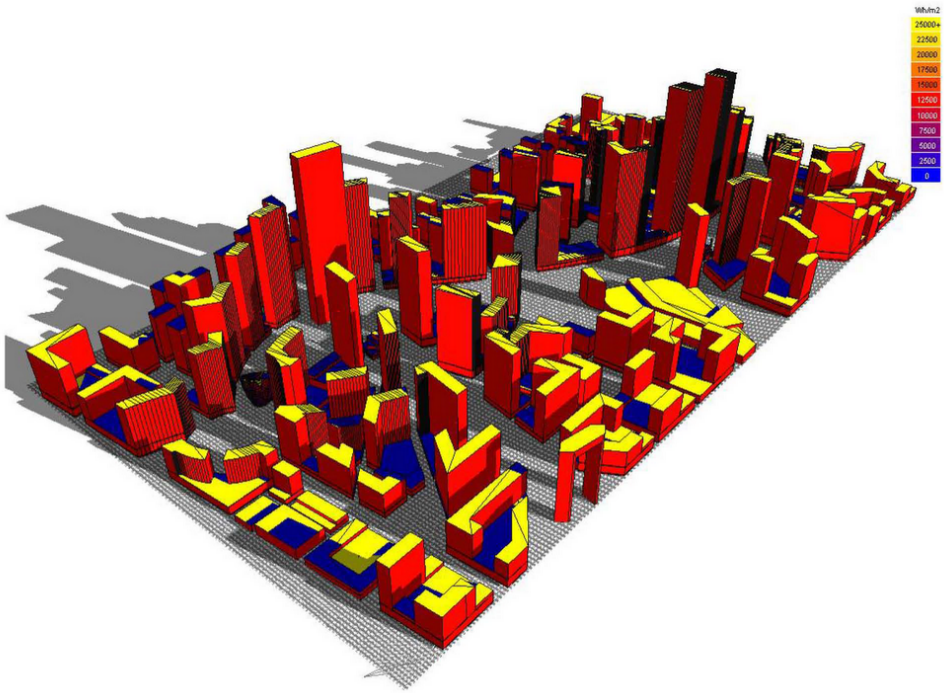



***Figure 2.2:*** *Solar Analysis in Sketchup and Ecotect. via omarohelmy.blogspot.com*

Related work of professional thermal performance analysis is usually done by professionals in building performance disciplines. Because of the delegation, the importance of thermal performance tends to be ignored by architectural designers. "Architects form an integral link in the design of efficient buildings. Energy-efficient design strategies therefore, require architects and engineers to work closely together in optimising the building shell. However,

this is not always practical. Architects must therefore, be able to perform a preliminary thermal analysis if energy efficient design strategies are to succeed. Existing tools do not cater for them or fit their design methodology. A need therefore exists for a simplified thermal design tool for architects." (Ellis and Mathews, 2001). The accurate, versatile and complicated tools are mainly developed for building performance practitioners, who are trained to do thermal and other building related analysis. The analysis results produced by such tools can reflect meaningful points while they usually lack graphic interface, which result in additional work of visualising the thermal data. If the practitioner is not good at the visualization work, it will be difficult for them to collaborate with architectural designers to read the analyse results and make improvements.

There are numerous software for thermal analysis in the market from different developers for architectural designers and engineers to use, however, as expressed according to a survey, "suggested criteria are critically reviewed and tested. The final results indicate a wide gap between architects' and engineers' priorities and tool ranking." (Attia et al., 2011). Commercial thermal analysis tools are divided into two divisions, one is simple but lacking in accuracy, the other is accurate but complicated, sometimes with no visualization, and takes great efforts to learn and use. The former one is mainly in the form of plugin to other modelling tools for architects' use, so that it can benefit from the existing visualization, with an intention of reflecting effects of real-time changes and arrangements in relation to the thermal analysis. The later one comes as independent software for building information or thermal professionals. Such difference between analysis tools can easily run into an asymmetry view of the analysis and results during the work and communication between designers and engineers.

### 2.1.3 Data Visualization in Architectural Design Industry

Data science with mining, visualization and analysis techniques has been developing in recent years as a byproduct of the spanking growth of the Internet and Information

Technology, which enables the visualization and analysis of environment and building related data in the design process to make it more intuitive, persuasive and objective. "Analysis has been an integral part of the building design process. The process incorporates the need for site analysis at the very outset. This is followed by a comparative analysis of various design options aesthetically, functionally, economically and more recently on the basis of environmental performance." (Srivastav et al., 2009). With data visualization techniques, architectural designers are able to use data to justify their architecture projects, do modifications and presentations to clients. Every improvements brought about by any changes to the architectural model can be visualized vividly on the designer's screen and they can reason over different trade-offs by just flipping the details.

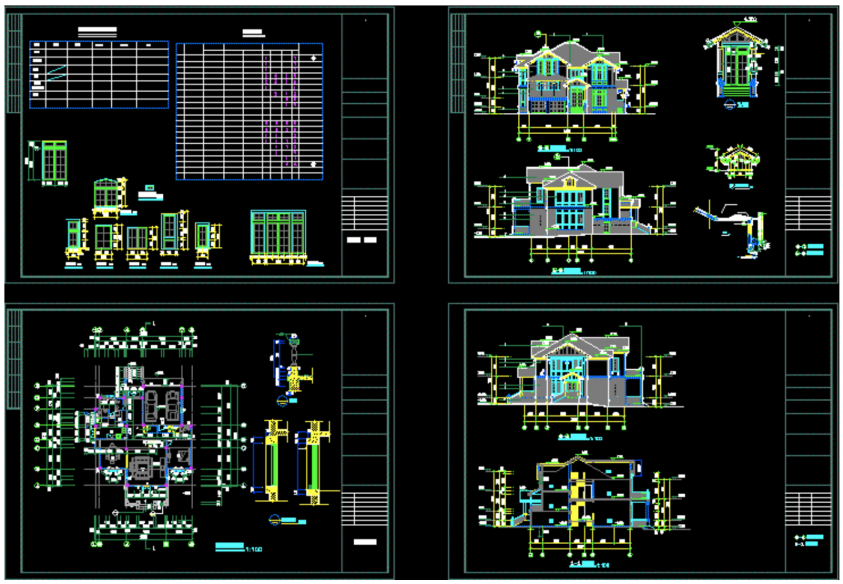


***Figure 2.3:*** *A house project in AutoCAD, via bibliocad.com/en/library*

A new trend of Building Information Modelling(BIM) has emerged since the beginning of this century, which is in application or in transition of application among an increasing number of architecture firms. Building Information Modelling is redefining the architectural and building industry in all aspects regarding efficiency, accuracy and collaboration of different professions. "The transition from traditional Computer-Aided Design to virtual building design phrased as Building Information Modelling, has created a tremendous

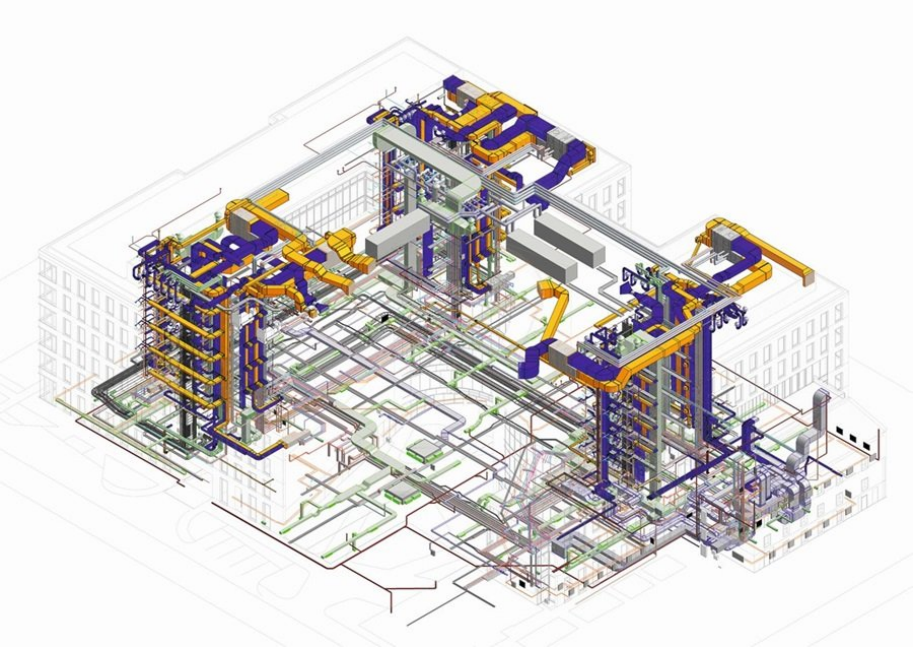


***Figure 2.4:*** *3D model of an office building, via wsp.com/en-PL/services/building-information-modelling-bim*

potential to realise more accurate and controllable design processes." (Krakhofer, 2015). As shown in Figure 2.3, the CAD illustration of a single house project with heating, ventilation, electricity and other thermal-related infrastructure is abundant of layers of different lines, which might results in confusion. While in Figure 2.4, the BIM model of an office building whose structure and space should be more complicated than a single house is more clear and readable in infrastructure and arrangements.

### 2.1.4 Virtual Reality for Computer-Aided Design

Virtual Reality(VR) has experienced a paradigm boost since Jaron Lanier found VPL Research and developed related gears such as goggles and gloves for the requirements of experiencing virtual reality in the mid-1980s. Virtual reality provides a novice interface for human-computer interaction which enables watching, listening and manipulating the simulated environment exactly in the same way human beings act in the real world (Mazuryk

and Gervautz, 1999). Once equipped with headset and controllers(or 3D mouse), users can experience whatever has been created inside the virtual environment no matter existing in real world or not.

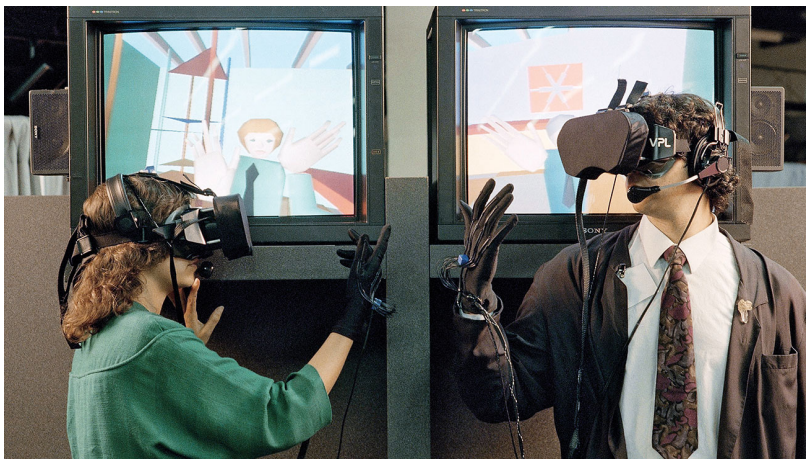



***Figure 2.5:*** *Two people demonstrate the EyePhone system which uses special goggles and a DataGlove which allows them to see and move objects around in a computer created environment, VPL Research, June 7 1989*

However, as one of the wearable technology that is still popular under research and development, virtual reality does have drawbacks such as the headset is too heavy to wear for hours and the quality of the view from the headset is not as good as what human eyes can see, it is still a promising tool for industry and entertainment use. Especially in the era of post-COVID, online and virtual working or collaboration are becoming a new daily routine which is great to reduce the exposure to the virus but increasing the difficulty of efficient communication. Virtual reality provides a solution to the collaboration dilemma that co-workers can enter the virtual environment to meet, view and discuss issues they are collaborating on.

There is an increasing number of research on the professional application of virtual reality in architecture that exploring all aspects from interactive and immersive design, analysis,

experience to training and education, which has constructed an excellent ecosystem for designer-use virtual reality.

## 2.2 Technology and Tools

This section discusses and lists the technology, equipment and tools in relation to the topics of this thesis research, including virtual reality, thermal analysis, modelling, and data visualization.

### 2.2.1 Virtual Reality Headsets

A virtual reality device contains a headset, 3D mouse(s), tracker with input and output data streams which connecting the front-end environment with the back-end computing engine. Nowadays, the device is generally named as virtual reality(VR) headsets.

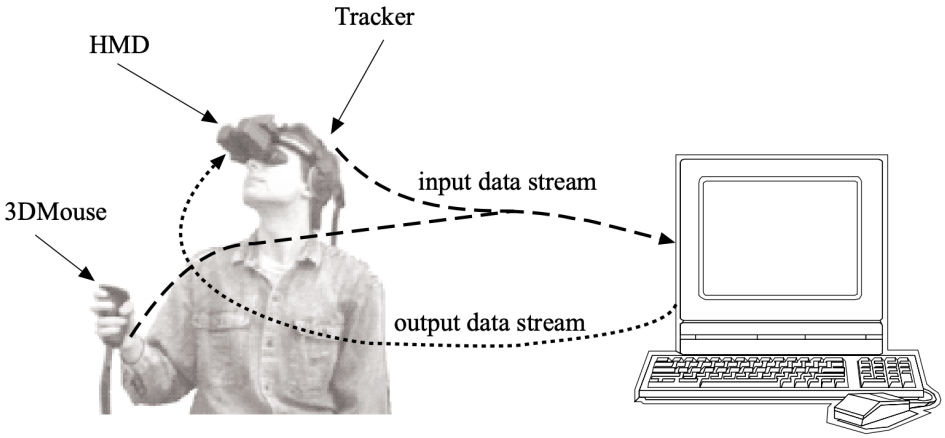



***Figure 2.6:*** *Basic Components of Virtual Reality Application. (Mazuryk and Gervautz, 1999)*

After a commercial investigation, several technology and hardware companies are engaged in seizing the virtual device and experience market. Among the highest ranking list, there

are Oculus VR from Meta, Vive from HTC, PlayStation VR from Sony and Valve Index from Valve. Below is a shallow technology dive of these virtual reality headsets.



***Figure 2.7:*** *Oculus Quest 2*



***Figure 2.8:*** *Sony PlayStation VR*



***Figure 2.9:*** *Valve Index VR*




***Figure 2.10:*** *HTC Vive Pro 2*

1). Oculus Quest 2

This most up-to-date VR version developed by Oculus can provide a full six-degrees-of-freedom (6DOF) experience and a more accurate motion tracking which is more immersive with a powerful processor and sharper display. It is smaller and lighter than previous versions and it is not cable-required. There are Oculus Store and Oculus Link available as software supports. The drawback of this headset is its short battery life.

2). Sony PlayStation VR

Instead of personal-computer (PC) based, this headset developed by Sony PlayStation is based on the PlayStation 4 (PS4 or PS4 Pro), which results in some restrictions for developers. However, it is compatible with non-VR apps and games and is motion control supported.

3). Valve Index VR Kit

Valve Index VR is the most expensive one in this tech dive. It provides an extraordinary 120Hz refresh rate which is able to deliver smooth motions with novice, immersive and finger-tracking controllers. This VR kit is based on SteamVR, where there are numerous VR software available.

4). HTC Vive Pro 2

HTC Vive Pro has the best resolution for VR experience with smooth motion tracking. It is also compatible with the innovative controllers from Valve Index. Along with the Viveport ecosystem provided by HTC, this pro version is designed for not only consumers but also professionals with SteamVR compatibility.

### 2.2.2 Thermal Analysis Software

There is a huge number of software which is either used for thermal analysis or having the features of thermal analysis nowadays. Here, an overview of some thermal analysis tools varying in proficiency, accuracy and complexity is provided for further utilization and comparison.

1). LadyBug Tools

LadyBug Tools consist of a set of analysis tools including Ladybug, Honeybee, Butterfly and Dragonfly, which has constructed an excellent ecosystem as a plugin to Rhinoceros and Grasshopper.

Ladybug is for detailed climate and environmental analysis with interactive visualizations; Honeybee is responsible for the creation, operation and visualization of daylight simulation with Radiance, OpenStudio and Therm as the core for energy modeling and heat flow envelop. (LadybugTools, 2012)

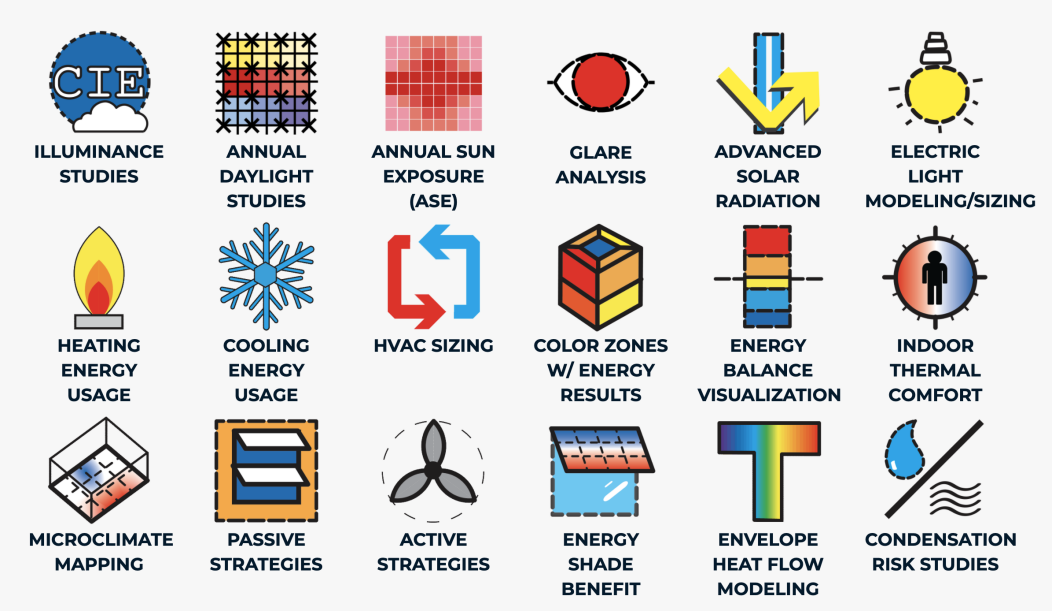



***Figure 2.11:*** *Features of Honeybee, via https://www.ladybug.tools/honeybee.html*

Butterfly supports advanced computational fluid dynamic (CFD) simulations using OpenFOAM as a plugin and python library; Dragonfly provides large-scale modeling and analysis such as urban scenarios. (LadybugTools, 2012)




***Figure 2.12:*** *Features of Butterfly, via https://www.ladybug.tools/butterfly.html*

All of the Ladybug Tools are widely used among educational and industrial architectural institutions and corporations which is due to the well-designed user interface, interaction and core features. It provides easy-to-use and hands on tools for architects to efficiently generate reasonable analysis on their design projects.

2). TRNLizard

TRNLizard is a plugin to Rhinoceros and Grasshopper that provides thermal and daylight building simulation based on detailed 3D geometry with the Trnsys 18 as the core. User can conduct design studies in detail, such as simulations and evaluation of simulation results, with predefined templates and outputs. This tool is modular structured and quite flexible, with whose components and features are adaptive to the developments and optimization of Trnsys. As a plugin tool, TRNLizard is able to make full use of both parametric modelling and building simulation. (Transsolar, 2017) Both are plugins to Rhnioceros and Grasshopper, LadyBug is more versatile while TRNLizard is more accurate and professional.

3). ClimateStudio

ClimateStudio is a new tool developed by Solemma LLC as a plugin to Rhinoceros. It supports environmental analysis workflows of daylighting, electric lighting, and conceptual thermal simulation (Solemma-LLC, 2020).

The core engine lying inside the thermal analysis features of ClimateStudio is EnergyPlus whole building simulation program funded by the US Department of Energy. The functionality is exactly the same as what EnergyPlus provides, however, the user interface and interaction approach is in a more modern and clear way than EnergyPlus.

To deal with simulation results, ClimateStudio provides a "Results Panel" as an interface for loading simulation results which are saved as .CSR files and displaying their contents (Solemma-LLC, 2020). This "Results Panel" is able to visualize simulation results in different graphs and the Rhino viewport with comparison support.

Another point worthwhile to notice is that ClimateStudio is fast and accurate because of its "noval RADIANCE-based path tracing technology" (Solemma-LLC, 2020). Radiance is implemented by ClimateStudio in a progressive path tracing mode so that the path

generation process is in real-time mode instead of pre-computing mode, which enables updating results gradually (Solemma-LLC, 2020).

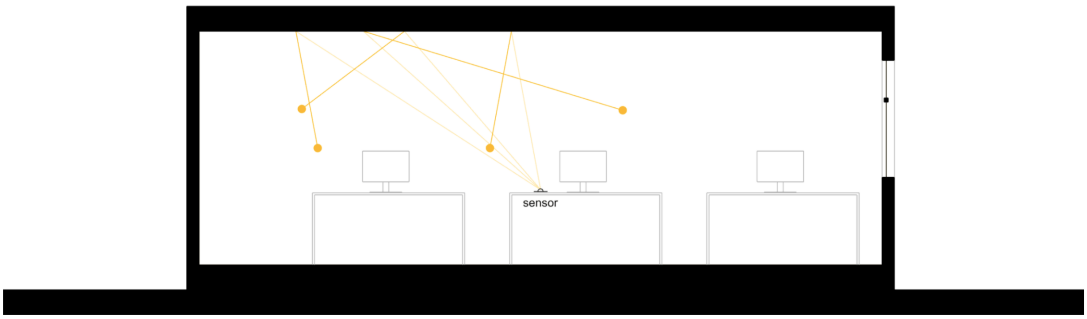



***Figure 2.13:*** *Path tracing process with Radiance, via solemma.com/climatestudio/speed*

4). EnergyPlus

EnergyPlus is the most basic whole building energy simulation tool for both professional and academic use. It reads input, computes accurate results according to algorithms, defined parameters and rules, and writes output as text files. The weakness is that there are no modelling and interaction interface to view inputs, results and outputs so it is not that popular among architects and architectural students.

Nowadays, more and more tools are developed based on EnergyPlus so it becomes less and less necessary for architectural designers to use EnergyPlus to do thermal simulation directly.

5). DOE-2

DOE-2 is a building energy analysis tool for engineers. It provides a detailed calculation of hourly building energy utility and cost according to weather data, building layout, constructions, usage, conditioning systems and utility rates (DOE-2, 2008).

Engineers can get detailed and accurate analysis results by using DOE-2, while it is too professional for designers to master and use for every design projects. It will take great

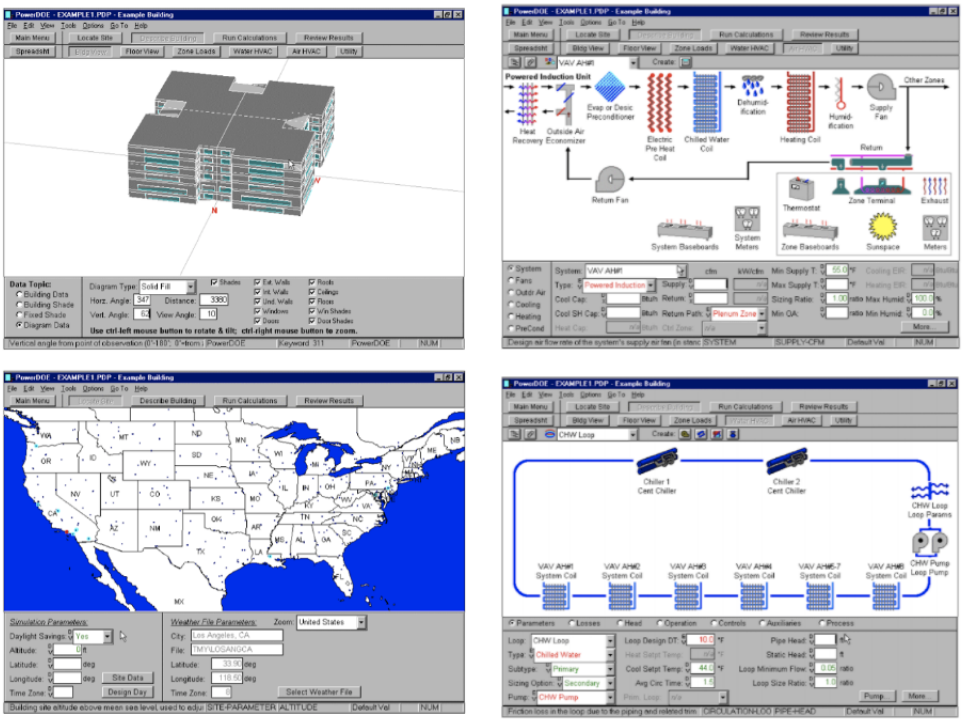


***Figure 2.14:*** *Some features of DOE-2, via doe2.com/Download/Docs/D22PDSum.PDF*

time to learn the features provided by DOE-2 and also cost a lot if designers calculate such detailed information for every design change. The user interface is designed professionally for engineers with a lot of graph with data and machine illustration and the information is not very straightforward to reflect the benefits from design change for designers to read and compare the trade-off.

### 2.2.3 Visualization Tools

Data analysis and visualization has become a significant topic with the development of graphics and statics and the widespread of portable electronic devices like cell phone, tablet and laptop. Data visualization is categorized according to dimensions, approaches and interactions. A relatively new but effective way of visualization is dynamic and immersive visualization, which represents data using dynamic visual effects and enhances the interac-

tion between data and human beings. Here is an overview of tools which have the potential to provide such visualization experience.

1). Processing

Processing is a coding platform compatible with several popular programming languages such as Java, JavaScript, Android, .Net and Python, and provides great visual art effects. It is widely used by numerous students, artists designers and researchers for learning and prototyping (Processing, 2001).

Processing provides a bunch of basics for prototyping such as Arrays, Camera, Color, Control, Data, Form, Image, Input, Lights, Math, Objects, Shape, Structure, Transform, Typography and Web, enables user to create colorful, recursive and dynamic visualization effects with data structures and transformations based on input data sets, mouse and keyboard events and camera.

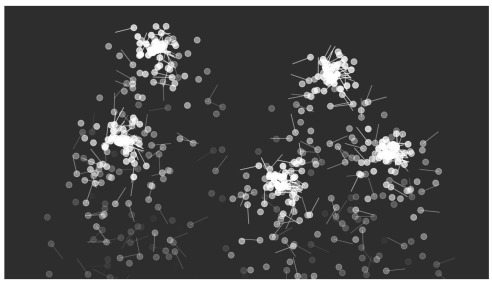


***Figure 2.15:*** *Dynamic multiple particle systems, via processing.org*



***Figure 2.16:*** *Saturation with mouse tracking, via processing.org*

Owing to the basics, Processing is able to provide a great ecosystem to take random input data sets and uses user-defined algorithms to visualize the data in customized rules, which qualifies itself to be an appropriate and easy-to-use tool for dynamic visualization. Once the visualization algorithm is defined, no matter what input data sets are, reasonable results can always be generated in the preview frame. So it saves a lot of work if users need to

generate visualization of different data sets on their own using tools like Adobe Photoshop and Adobe Illustrator.

2). Adobe After Effects

After Effects is a software providing tools for users to create industry-standard motion graphics and visual effects.

Different from Processing, After Effects is a comprehensive, professional and industrial tool with almost all the features related to animation and effects, including plug-ins, scripts and extensions which extend for advanced features, commands, and special approaches of interactions. User can either create animations from scratch in after effects or load video clips to after effects and add or edit effects inside.

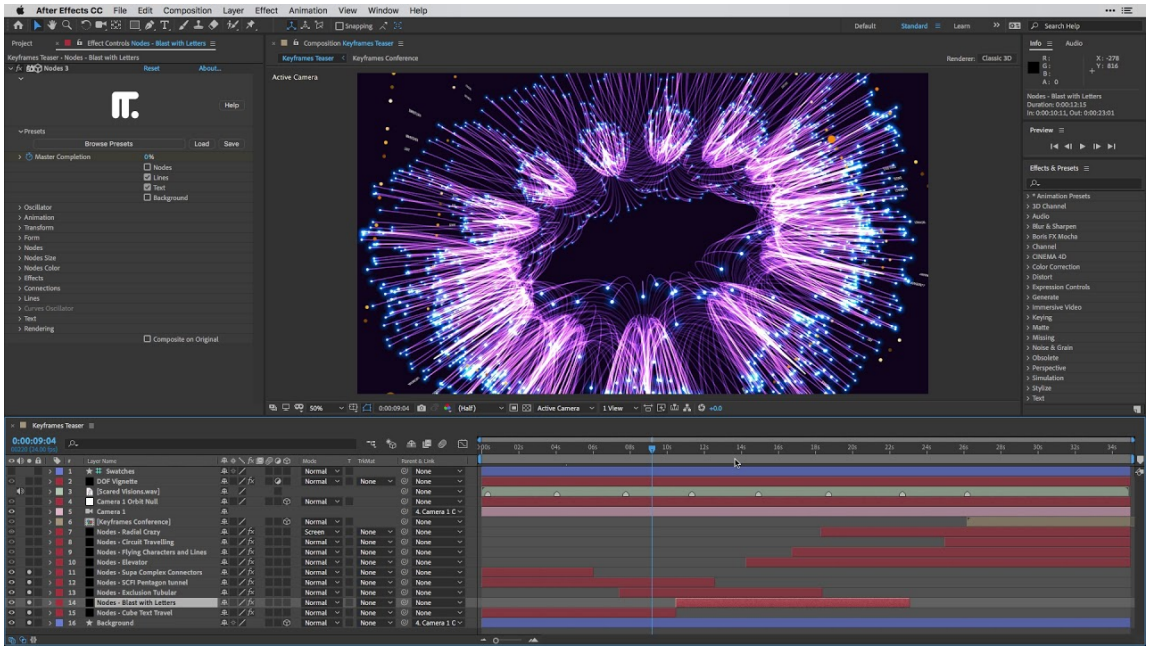


***Figure 2.17:*** *Data visualization using After Effects and Nodes3 from yanobox, via youtube.com/watch?v=LBRZQdzRPfs*

Because of its ample and versatile functionality, After Effects has become a good option for data visualization of all industries. Users can load data sets, define rules and algorithms

with plug-ins , extensions, and scripts, and generate colorful and dynamic visualizations. They can also process video clips such as editing and superimposing them together within After Effects.

So it is reasonable to say that After Effects can either process the animation results generated by Processing or be a complicated version of Processing. With the embedded tools, users can create whatever visual effects they want using After Effects.

# 3 Related Works

This chapter documents an overview of the selected works that relates to this research in topics, approaches, tools and so on. In the overview, similarities and comparisons between the cases and this research are discussed to further identify the gap and contribution of the research project.

## 3.1 Sound Space

Sound Space is an interactive virtual reality tool to simulate and visualize room acoustic implications for architectural designers (Gehron et al., 2019). This project explores the utilization of sound as building information and visualize this building information in game engine-based interactive virtual reality experience.

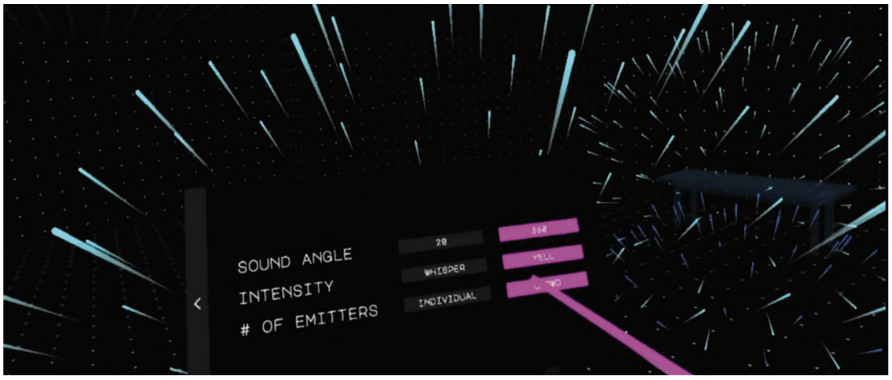



***Figure 3.1:*** *User interface and interactive sound wave (Gehron et al., 2019).*

This research focuses on the evaluation of acoustic performance for buildings especially those with the functionality of theatres and symphony halls and even schools, hospitals or museums. It aims at providing a accurate and interesting enough tool for architects and designers to evaluate acoustic effects in their design projects, so that professionals can find related issues earlier and do modifications accordingly afterwards (Gehron et al., 2019).

The similarity of Sound Space and this thesis research lies in three points. One is the intention of emphasizing the significance of building performance such as acoustics and thermal performance in design process for architects and designers. Another is the methodology of embedding core simulation engine into virtual reality environment to create a novel workflow and desktop prototyping tool for dynamic, interactive and 3D immersive visualization experience. The last is their common focus on pursuing the accuracy and efficiency of the real time simulation and its results.

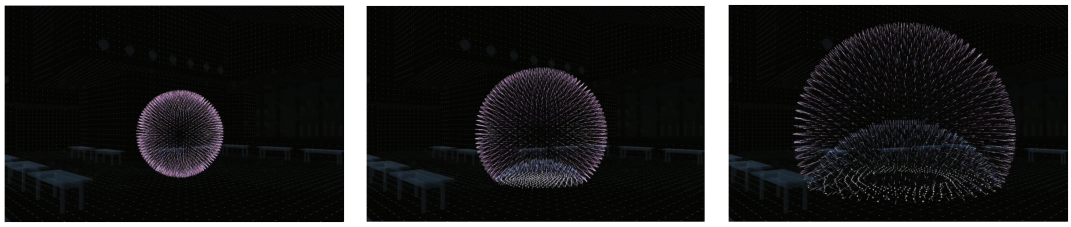


***Figure 3.2:*** *Sound wave simulation of a point sound source (Gehron et al., 2019).*

There are several things which are worthwhile to take away from the Sound Space project that might be beneficial to the prototyping of this thesis research.

Firstly, there are trade-offs between the simulation result and the computation speed. So the Sound Space simulation engine only requires a few inputs such as room geometry, material of room surfaces, and a sound source to simplify the data processing stage. It also assumes all collisions will result in specular reflections instead of diffuse reflections without regards of its material properties to maintain computation speed and simplicity of the system (Gehron et al., 2019).

Secondly, Sound Space uses Unity3D game engine as the computing core to improve the performance of the system and enable real time simulation. The initial implementation in Rhinoceros and Grasshopper is based on early and late reflections which makes the results a little bit out-of-date. So the team alternate the implementation in Unity3D and rebuild the system to simulate early reflections and scatter the sound effect previous to the display of

late reflections, which enables a real time sound visualization (Figure 3.3) (Gehron et al., 2019).

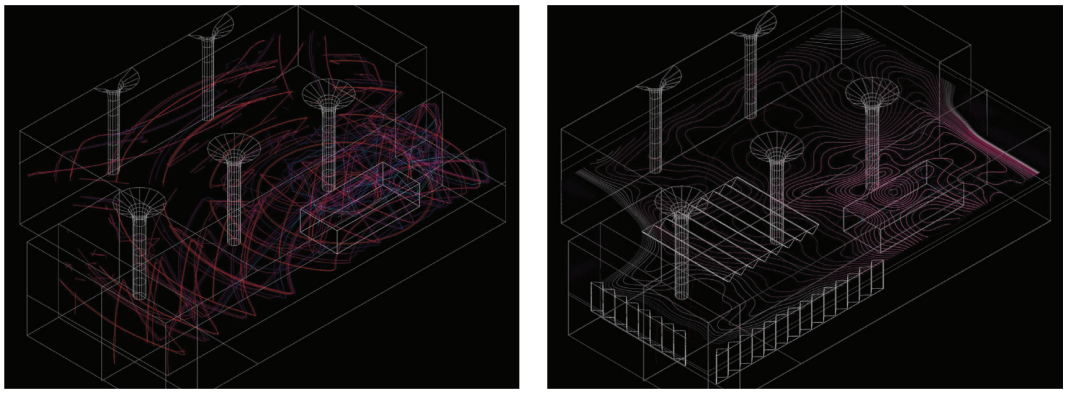


***Figure 3.3:*** *Acoustic simulation diagram and resulting sound contour map with decibel levels (Gehron et al., 2019).*

This is an excellent example of providing an engaging approach for designers to pay attention to physical data and performance during the design process. The interface of the prototype is attractive, vivid and align with aesthetics, the system is easy to use and the simulation result is reasonable and accurate. Sound Space is an enlightenment for all types of building information to create similar tools to do good to architectural design education and industry.

## 3.2 Virtual Reality Indoor Condition Live Sensor

This paper proposes a workflow with the integration of environmental sensors, Building Information Modeling (BIM), and Virtual Reality to collect environmental data, build information model, and represent building indoor environment conditions in the immersive 3D experience (Natephra and Motamedi, 2019).

As is vividly illustrated in the following figure (Figure 3.4), the whole project can be viewed as 3 parts from collecting real time building informative data with IoT(Internet of Things)

sensors, constructing BIM model with extracted geometry and information, to simulating the virtual environment for users.

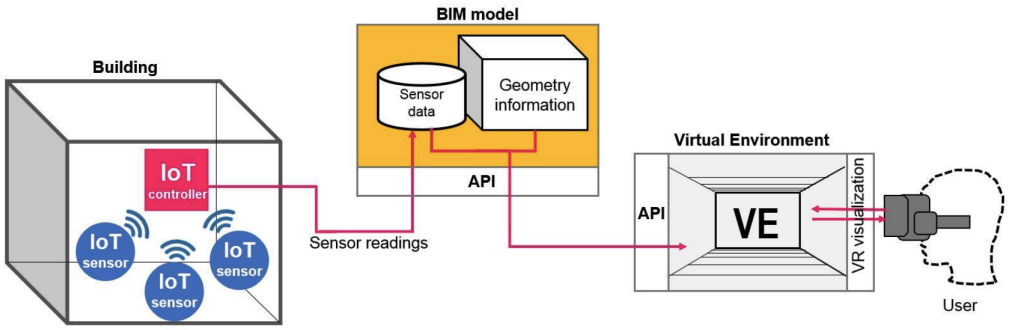



***Figure 3.4:*** *Project framework overview (Natephra and Motamedi, 2019).*

The most innovative points are that this research successfully constructs a workflow connecting data, model and visualization with Arduino sensors, IoT, BIM, and VR, which are all up-and-coming technology in the industry (Figure 3.5).

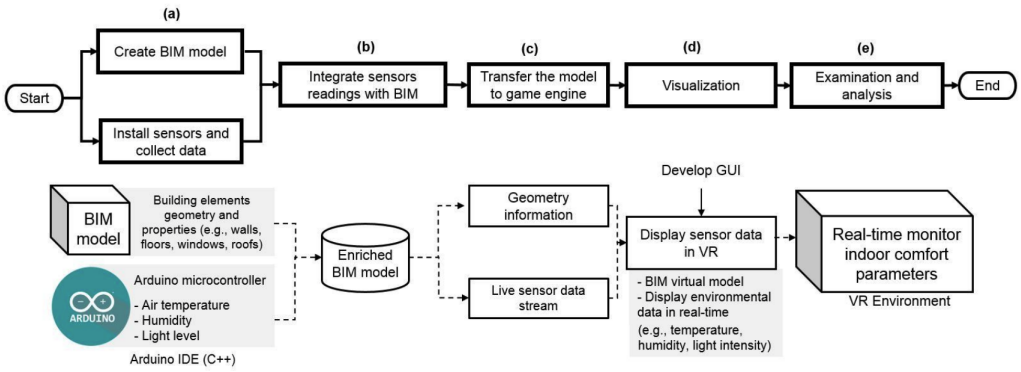



***Figure 3.5:*** *Workflow of integrating sensors, Building Information Modeling (BIM) and Virtual Reality (Natephra and Motamedi, 2019).*

It requires great effort to get familiar with each of the technology and utilize them in proper ways. As documented in the paper, there do be challenges and limitations which are worth noticing for future research and projects. For example, incompatible data types will result in invalidity of data sets; APIs (application programming interface) provided by the company

who created the technology are not always useful and sometimes it is necessary to develop data pipeline according to the specific project requirements.

A thorough case study is conducted as an experiment using the prototype and detailed data results are provided in the paper. During this process, sensor readings are communicated with BIM by Firefly and stored in Dynamo. Simultaneously, sensor data is retrieved by a plug-in that supporting Arduino in Unreal Engine and transferred as numerical values to Unreal Engine for data visualization.

This research focuses on the construction and representation of the innovative workflow so there is little emphasis on the data processing and the visualization part is desolate. Inside the virtual environment, data is visualized as numbers in the view instead of diagrams or other indicators. Different from this project, the virtual visualization experience part of the proposed thesis research can be a center of exploration by analysing visualization tools and professional software.

## 3.3 Augmented Reality Design Decision Support Engine

This project is aimed at enabling comparability and evaluation of decision making at the early building design stage by supporting data collection, characterization and visualization through Augmented Reality (Krakhofer and Kaftan, 2015). A customized Augmented Reality framework prototype is developed which enables data accessibility, visualization, and is able to serve as "a collaborative decision support engine" (Krakhofer and Kaftan, 2015).

Normally, there are tremendous back and forth processes among early stage of building design because of the endless analyses and iterations of space, environment, economy, and form finding, which will generate a huge amount of data. It is critical to collect and

store these data sets according to the design iteration version so that they can be accessed and reviewed for comparison and evaluation (Krakhofer and Kaftan, 2015). Therefore, interactive and visual-based Augmented Reality is applied with an OpenGL based viewer and a flexible user interface developed using Java.

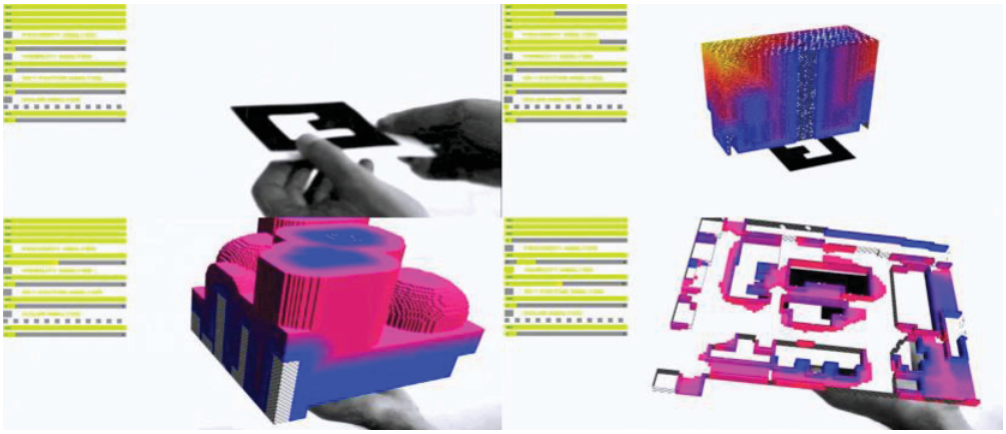


***Figure 3.6:*** *User interface and analysis of the AR engine (Krakhofer and Kaftan, 2015).*

From the user interface and the example of building thermal analysis (Figure 3.6), this prototype provides a navigative interface among iteration versions with customized 3D section views. It gives a hint to the thesis project that there can be different views and model iterations existing in the system at the same time instead of only a single view (Krakhofer and Kaftan, 2015). In addition, although carried out in 2015, the color panel of the thermal analysis looks still clear and good enough for today. It is a decent way to choose different colors with opposite hue and the similar saturation with aid of gradual differences to smooth the difference and highlight the thermal conditions.

## 3.4 CAD Workflow of Thermal Simulation and VR Visualization

This research with a focus of thermal simulation and visualization for building design optimization was conducted in 2013 and has the most similar topic and workflow with this

thesis research with the utilization of Computer-Aided Design (CAD) tools and Virtual Reality.

It provides a paradigmatic workflow from creating energy model of design project and setting up data collection as first stage, second stage including providing measurement assumptions and updating input, and presenting the building model, identifying performance problem, and making adjustments as the last stage. This is worthwhile for current researches to learn from (Bahar et al., 2014).

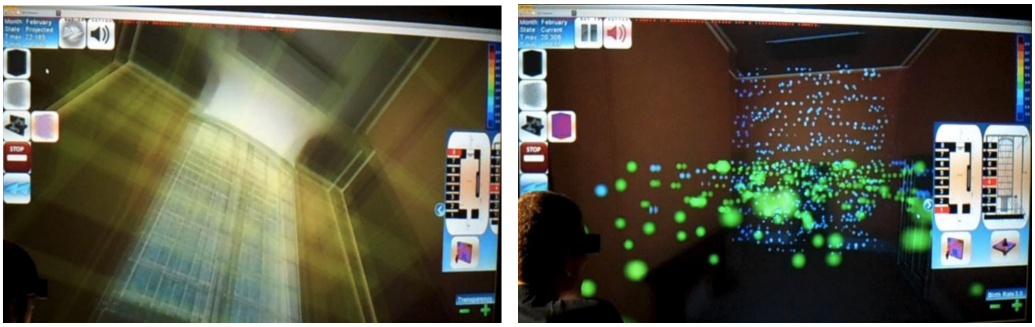


***Figure 3.7:*** *Visualizations of thermal metaphors with transparent cubes and particles (Bahar et al., 2014).*

Lastly, it is creative for the research project to visualize thermal data and performance with transparent cubes. It is an approach of abstraction and simplification that not only eases the representation and visualization but also adds to the readability of the visual results in virtual environment.

# 4 Research Question and Hypothesis

This chapter declares the research question and gap from existed research and projects in detail with a hypothesis that aims to answer the question. This part is constructed on the basis of the previous background and related works chapters, and serves as a trigger of the following discussion of methods, prototyping, and conclusion.

## 4.1 Research Question

The research question of this thesis project is how can Virtual Reality and existing thermal analysis tools be combined to provide interactive and immersive thermal data visualization experiences for architectural design professionals to utilize in early stage of compact urban residential building volume design.

This question can be decomposed into the following four sub questions with detailed discussion.

1). How to interpret and visualize the thermal data for the maximum use of early stage of building volume design? Thermal data can be classified into several themes such as heat, airflow, temperature, humidity and so on. In both conceptual and realistic meanings, those data sets have different impressions and common interpretation ways. The requirements of the size, species and granularity of the interpretation of data sets in architectural design are varied in different design stages. In the early stage of building volume design, what kind of interpretation and visualization way is most meaningful is worth exploring for further steps of research.

2). How to quantify and compute the thermal related building performance and reflect on the visualization results? Thermal related building performance is quantifiable in consideration

to numerous studies on building performance these days. In the circumstance of virtual reality, how to quantify and compute the thermal related building performance intuitively for reflection on the visualization results for architects instead of BIM specialists that are more professional on those data and charts is a more detailed and oriented question for research.

3). How to design the interface and present the data to adapt to the interactive and immersive environment? At the same moment of virtual reality providing an immersive environment for users, an interface comes into being. The behaviors of humans interacting with data sets and visual effects presented by virtual reality all take place throughout the interface. In such a context, it is critical to design an interface which is oriented to the professional early stage building volume design and adaptive to the highly interactive and immersive environment.

## 4.2 Gap Identification

There have already been countless researches on the topic of application of virtual reality in architecture and building industry, varying from immersive architectural experience to haptic modelling to collaborative designing. However, the developing immersive visualization and building performance computing features still have remaining space for further exploration.

Building information and simulation have escalated to a popular topic related to architectural design during a residential building's whole lifetime from design, construction to use in order to improve the living comfort in the recent years. While those evaluations and standards usually get involved in the design process at a relatively later point. In fact, in the early stage of residential building design, especially volume design, if related data sets such as thermal data are proactively taken into account with urban context, site information and

aesthetic consideration, the positive impacts brought to residence comfort can be at least as much as those efforts made by passive remedy operations such as adding ventilation and insulation.

It is true that there is a large number of visualization tools for professional architectural design use, which can provide 2D visualization results such as charts or tables based on drawings or 3D results based on models vividly. Both of them should be viewed through the interface of software and computer screen. Therefore, the visualization tool based on virtual reality which can provide quantified performance parameters and enables professional users to intuitively view, do modification and compare the design results under specific data sets in an immersive and interactive environment remains relatively unexplored.

## 4.3 Hypothesis

A prototype is designed as a proof of concept and developed to test the general hypothesis as follows. Experiment and survey are conducted to verify the effectiveness of the prototype and the hypothesis as a reflection of the effectiveness whole research process.

First of all, through the virtual reality based interactive visualization engine, thermal data and performance can be computed and visualized more intuitively and expressively inside the virtual environment. With the functionalities of visualization and modification of design models, thermal-related design decision making in the early stage of compact urban residential building volume design can be provided with more effective support.

Secondly, attention of architectural professionals about the importance of thermal considerations in an earlier stage of design can be drawn by experiencing thermal visualizations inside the virtual environment provided by the prototype.

# 5 Methods

As discussed in previous chapters, a system was developed as a prototype to verify the proposed hypothesis. This chapter documents the prototyping process and workflow, along with design, implementation, technical details, and experiments.

## 5.1 Overview

This prototype contains the following problem domains with relations demonstrated in Figure 5.1.

The system requires site information and physical data as input parameters and provides simulation and visualization choices for users to choose from. After input data and customized choices are all set, Unity3D as the virtual reality engine will compute the results and present them inside the virtual environment. In addition, user can modify the site model and design model in the virtual environment using Virtual Reality handlers, and then Unity3D will generate updated visualization results accordingly.

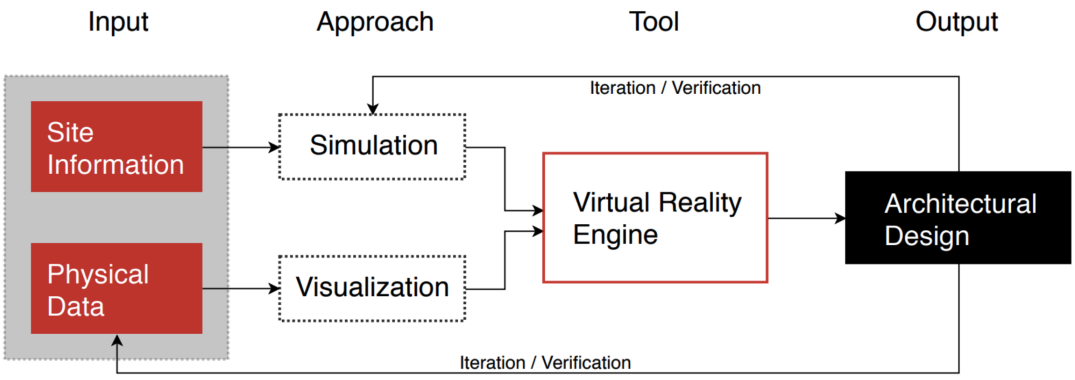



***Figure 5.1:*** *Problem domain and general process, drawn by the author*

## 5.2 Workflow

The project is aimed at providing immersive and dynamic real-time thermal analysis for professional users. The basic workflow of this prototype from the perspective of a user is as follows.

### 5.2.1 Load the design site and model(optional)

The first step when entering the system is to load a design site with or without the project design model. And there provides the following two options.

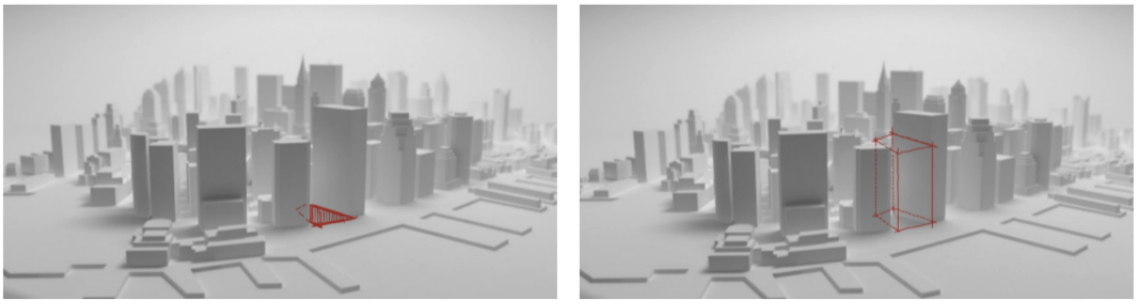


***Figure 5.2:*** *Load site model (draft diagram), drawn by the author*

a). load the site and design model from external. The imported model file should be in the format of .fbx to ensure efficient geometry interaction and updates between Rhinoceros3D and Unity3D.

b). create a naive site or model (e.g. several simple rectangles interpreted as buildings) with basic building blocks and the urban texture on their own with VR handlers inside the virtual environment. All the models created in the virtual environment are based on a cube unit to simplify all the process during the prototyping. In the create mode, every click will generate a new cube unit. User can rotate, scale, move and place the cube at will.

### 5.2.2 Load physical data

For the second step, it is necessary for the user to load physical data to the system. Useful data sets includes location, climate, weather, wind, humidity, sunlight and so on. Due to the inner visualization engine of Ladybug, the data set format should be .epw.

Data files in the format of .epw are weather data saved in the standard EnerpyPlus format. It can be used in simulation software which use EnergyPlus as their core simulation engine. It contains 35 parameters including temperature, humidity, atmospheric pressure, radiation, wind speed, snow and liquid depth.

### 5.2.3 Customized visualize

After design site and model are successfully loaded or created, there are visualize options for user to choose. User can choose the analysis granularity, analysis data type, and time frame through the interface triggered by the VR handler.

When customization is finished, the desired thermal visualization will be present in the virtual environment simultaneously. User can still control visualization parameters in the same time.

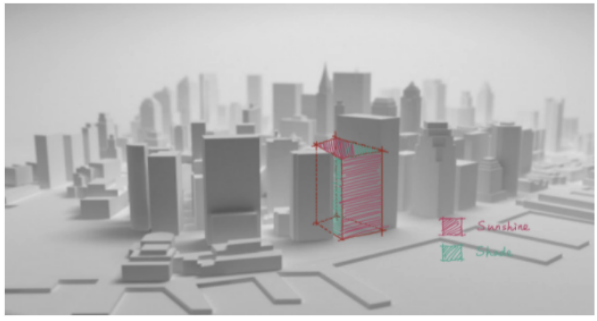



***Figure 5.3:*** *Visualize (draft diagram), drawn by the author*

### 5.2.4 Edit

With the temporary thermal analysis result visualized, in addition, user can view and edit the design model with the interactive interface which can be called out and conceal by left VR handler.

Since the design model is in the unit of cube, user can edit their design by adding, deleting, moving, placing, scaling, and rotating the cubes in the environment by interacting with the VR handler. The updated thermal analysis results will be visualized accordingly.

## 5.3 Data Set

As briefly introduced in the previous workflow overview, data sets from .epw file of different location can be loaded and used as the thermal analysis parameters to provide temperature, radiance, humidity, and airflow analysis and visualization. All of those data sets are visualized in the representation of different colors to ensure straightforward expressiveness and simplicity.

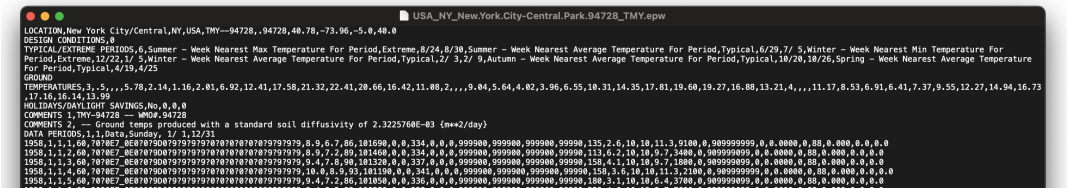



***Figure 5.4:*** *Screenshot of the epw file of Central Park, New York City, 94728, by the author*

Aside from the aforementioned data sets from the .epw file, Mean radiant temperature (MRT) is a key factor which is identified as the most primary effect of thermal comfort of a building. The definition of mean radiant temperature is "area weighted mean temperature of all the objects surrounding the body". (Bahar et al., 2014) The radiant temperature of a point is equal to "measured values of the temperature of the surrounding walls and surfaces and their respective positions to a human" (American Society of Heating and Engineers, 1996).

The following are three equations that can be used for buildings with surfaces and walls of relatively small temperature differences, free running buildings, and heated or cooled buildings separately.

1). Equation for buildings with surfaces of small temperature differences (American Society of Heating and Engineers, 1996):

$$T_{mr} = T_i F_{p-i} + T_i F_{p-i} + \cdots + T_N F_{p-N}$$

2). Equation for free running buildings with no heating or cooling (Nicol et al., 1998):

$$T_c = 11.9 + 0.534 T_o$$

3). Equation for buildings with heating or cooling (Nicol et al., 1998):

$$T_c = 23.9 + 0.295(T_o - 22)\exp([-(T_o - 22)/33.941]^2)$$

The mean radiant temperature data sets are calculated with loaded physical data sets and are relative to the location of the user in the virtual reality. The visualization is expected to change due to the movement of the user inside the virtual environment.

## 5.4 System Design Decisions

This section summarizes important design decisions made during the system design and implementation process with the intention of either narrow down the project or simplify the project to make the prototype more expressive and straightforward as a proof of concept instead of a well-developed software for widespread industrial or professional use.

1). Interpret input design models in a cube unit
As this prototype is designed for early design stage, the input building model should be really simple and succinct and cube representation will not result in loss of accuracy in such conditions. A cube unit can simplify the thermal calculation, analysis, and visualization process by avoid strange angles and intersections between surfaces and models. The initial cube unit has every edge of length 1 and users can modify the cube in create and edit mode of the system.

2). Round decimal values to integer values
Decimal calculation is a common point in computer science to result in problem due to conversion between binary numbers and decimal numbers. Such issue usually happens in the form of infinite loop in a computer program when encountering infinite and cyclic decimal values. To avoid software collision and calculation time, all decimal values are rounded up or down to integer values in this prototype project.

3). Every building in the system has only surfaces and walls
As we all know, besides walls, floors and ceilings, buildings in real life have healing and cooling systems, insulation layers, and material differences. Considering this research is aims at early design stage, it is assumed that all the buildings only have surfaces and walls with no differences.

4). Visualize thermal analysis results with color

Although there might be better ways to visualize thermal data such as using brightness of the scene to visualize the radiance, color is still the most realistic and expressive approach for the general user group due to the direct difference between different RGB color or HSB color. It will be easier to present and to identify.

## 5.5 System Framework

This section demonstrates the detailed framework of the prototyping system. It mainly covers how user communicates with the system by interacting with Virtual Reality headset and handlers, and how different system parts interact with each other to generate the desired results.

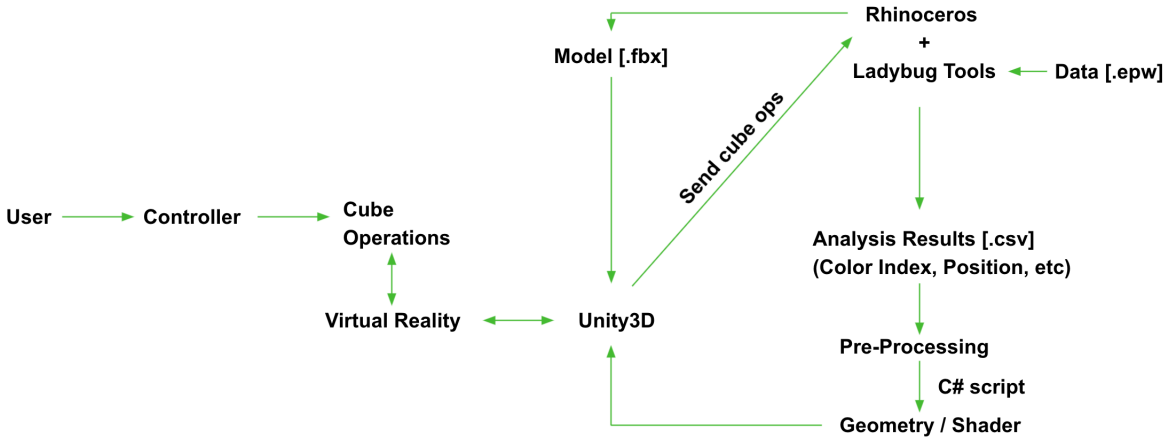



***Figure 5.5:*** *Prototyping framework, drawn by the author*

On the user side, once they are wearing the headset and holding the handlers, they directly enter the prototyping virtual environment, walk around and interact with the environment freely. After feeding site, design model and physical data to the system, they can choose defined cube operations through handlers to manipulate the design model. Last but not least,

they can view and experience the visualized thermal effects inside the virtual space and use cube operations again to improve their design in a rough cubic granularity.

In the system view, it will take in model and physical data, set them by keeping making remote procedure call with Rhinoceros and Ladybug Tools in grasshopper, get analysis results from Rhinoceros and do pre-processing on the retrieved data sets to provide visualization results such as geometry and shaders in Unity3D for user to experience in the provided virtual space.




***Figure 5.6:*** *Data and geometry interaction framework, drawn by the author*

Inside the system, on critical point is the connection between the game engine Unity3D and the modeling and thermal analysis engine Rhinoceros and Ladybug Tools. There are continuing data communications between these two sides due to cube operations and visualization requests happening in Unity3D and thermal analysis results generated in Rhinoceros and Ladybug Tools. So there is a necessity to introduce a middle ware to enable the continuous connection. A server is used as a delegated host to redirect and interpret those remote procedure calls generated by one side to the other side. It can be either local or deployed in cloud.

The server is backed up by a relational database so all the operation records and data sets can be stored to support recovery and avoid data loss because of power or system outage and crash. The database table contains three columns, "Operation", "Timestamp" and "Contents". "Operation" includes "ModelUpdates" or "AnalysisResults"; "Timestamp"

is the database time when the entry is stored; "Contents" are .csv files encrypting either updated geometry coordinates or thermal analysis data with coordinates.

If local server and database is used, the interaction can happen locally in the same machine that develops the prototype. If cloud server is chosen, there are several cloud service providers can be choose from such as Amazon Web Service(AWS) EC2 instances with DynamoDB, Microsoft Azure or Google Cloud Platform.

## 5.6 Interface and Interaction Design

This section briefly elaborates the interface and interaction design in relation with the prototyping system. Due to the time constraints and the prototyping intention as a proof of concept instead of a research on user interface and interaction, this part is not thoroughly organized and well developed. There is still room for improvements in different aspects, which will be further discussed in the limitation section of the conclusion chapter.

### 5.6.1 User Interface

In general, the user interface style is in a black and green theme. The background is in black, and other handlers, instructions, buttons, and models are in green. Models are represented as green wire frames since early stage models have fewer information than real building blocks.

Once entering the system, there is the home screen. The prototype name and logo are available with five interactive buttons. The buttons are "Load Model", "Free Mode", "Hint", "Start" and "Exit" which enable user to choose to load a model or create a site, get instructions as a starter, start or exit the system.




***Figure 5.7:*** *Home scene screenshot, by the author*

If "Start" button is clicked through the VR handler, the model scene will be presented. If it is free mode, the view is barely nothing with defined site border and lines for reference (Figure 5.8). If model mode is chosen, the view is the model in green wire frame with lines for reference on the ground.

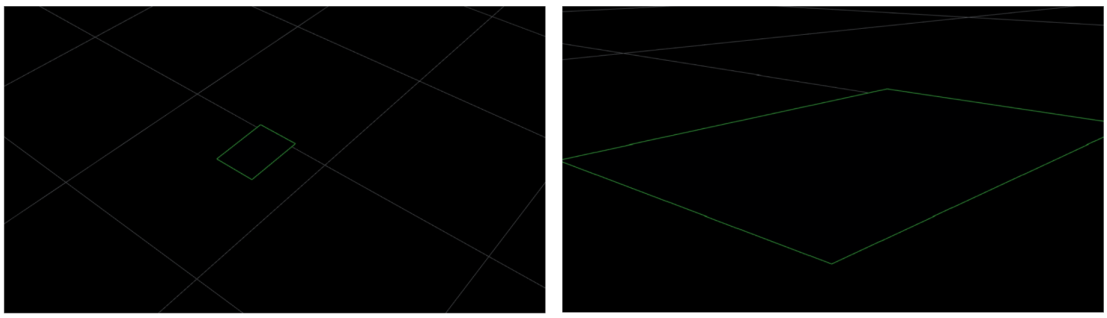


***Figure 5.8:*** *Free mode in aerial view and human-eye view, by the author*

This interface is in sketch status due to lacking in knowledge and experience of user interface design and Unity3D techniques. Otherwise, several indicators such as which mode the user is currently in, and reference bars can be added as floating objects in the virtual reality scene.

As an alternative and complement to the draft interface, an additional operation and status indication bar is designed which can be triggered by left hand VR handler to indicate current mode, view and available operations.




***Figure 5.9:*** *Operation and status indication bar, by the author*

### 5.6.2 Interaction

User interaction is developed based on the basic functionality of VR handlers. The interaction system temporarily assumed that users are right-handed to simplify the development process so interactions happening with left hand VR handler are mainly queries and play a role of assistance, while interactions with right hand VR handler are controls, operations, and decisions. During industrial development, a setting choice should be provided for users to choose whether they are left-handed or right-handed people.

The following is the detailed list of basic interactions provided by the prototyping system, including navigation, selection and manipulation in general. According to the design, an instruction of the VR handlers and interactions is provided in the "Hint" section of the system.

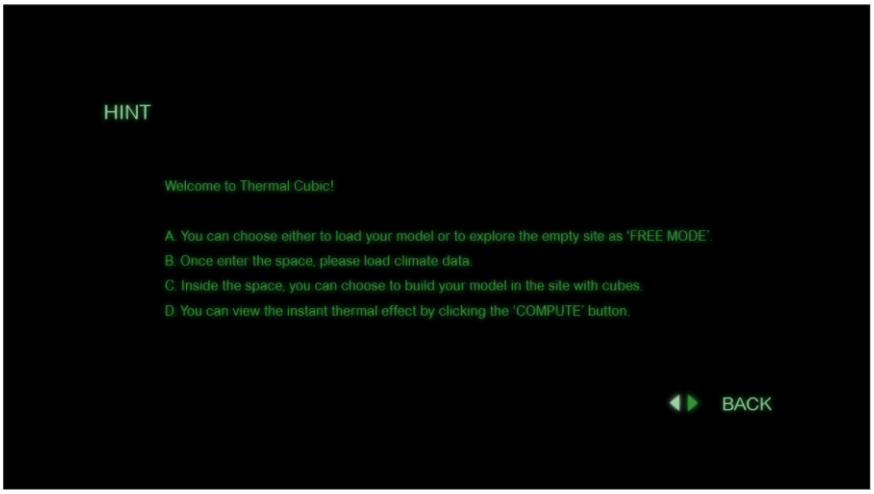



***Figure 5.10:*** *Hint scene screenshot, by the author*

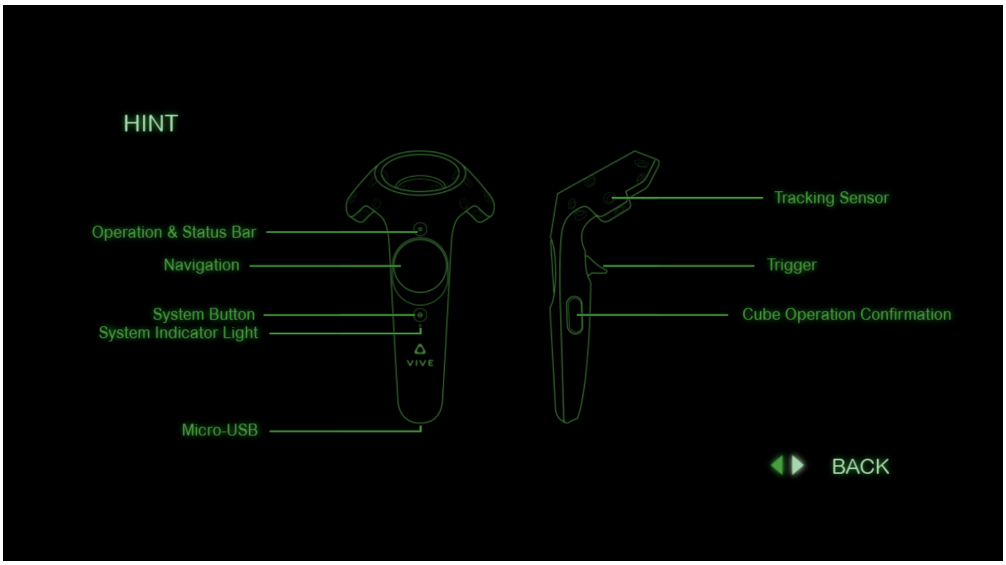



***Figure 5.11:*** *Interaction hint scene screenshot, by the author*

- Navigation

  User can navigate in the virtual space by walking around wearing the headset or by changing settings in the status bar which can be triggered by clicking the left hand VR handler.

  - Location/direction/view angle change

    Change of location, direction and view angle can be achieved directly by human body's walking, turning around and change head angle.

  - Altitude change

    Change of Altitude can be achieved by sliding the height slider in the status bar.

  - Aerial/human-eye View switch

    View switch can be achieved by clicking the "airplane" or "human" toggle in the status bar.

- Selection

  The system supports cube selection by clicking on the cube when the right hand VR handler omits green rays and the left hand status bar is concealed.

- Cube manipulation

  Cube manipulation is supported mainly through the status and operation bar. Different operations can be enabled in the operation section of the bar by clicking the corresponding icon using the right hand handler. All the following operations are in the condition of corresponding icon clicked.

  - Cube generation

    A new cube unit can be generated by clicking the right hand handler once. The cube will be generated in the same coordination as the right hand handler.

  - Cube deletion

    A existed cube can be deleted by first selecting the cube and then clicking once.

- Cube move/position

  A cube can be moved from one coordinate to another by hold and move the right handler. Similarly, a cube can be placed by clicking the right handler with the condition that there is a cube in the right handler. A cube can only be moved or placed to ground or above other cubes. It can not float in the air.

- Cube rotation/scale

  A cube can be rotated or scaled by holding the buttons of two handlers at the same time and do rotation or scaling posture. The cube can be either in the right handler or on the ground or above other cubes.

- Step back

  The system enables user to step back to previous status and uses an inner data structure to log the changes. But available previous steps are limited to three.

• Visualization

After data is loaded, thermal analysis resources are sufficient. Due to pre-calculation will cost a large amount of computing resources and result in longer waiting time, users have to choose several parameters to enable the analysis and visualization.

- Data set choice

  User can choose what type of data to visualize by clicking the desired data type in the status and operation bar.

- Granularity choice

  User can also choose the granularity of the visualization by clicking the desired data type in the status and operation bar.. Granularity will determine the color difference and visualization results. Different granularities are suitable for different building scale or visualization intention and can reflect different design issues.

- Date/time choice

  User can also choose the specific date or time and the time duration of the loaded data to do visualization by clicking the desired data type in the status and operation bar.

## 5.7 Technical Details

This section discusses and justifies the hardware and software choices and details in relation to the prototyping project.

### 5.7.1 Hardware

- HTC Vive Virtual Reality System x1

  HTC Vive Virtual Reality System is used as the virtual environment to provide immersive experience. This machine mainly consists of the following items.

  - VR headset x1
  - Base station x2
  - Wireless controller x2
  - Cable and links

  The system is installed in a 4m * 4m cubic room space with no occlusion and obstacles.

  Although it is heavy for long-time wearing and there are too many cables for the connection with desktop, it is able to provide great immersive Virtual Reality experience with high resolution and precise tracking and visualization.

- Desktop x1

  A desktop is used to connect HTC Vive System with supported software which will be discussed in the next sub section.

### 5.7.2 Software

- Windows 10

  The chosen operating system was MacOS previously but changed to Windows later due to their compability of Virtual Reality. It is nearly impossible to do Virtual Reality related



***Figure 5.12:*** *HTC Vive Virtual Reality System, via business.vive.com*



***Figure 5.13:*** *Virtual Reality equipment setup, photo by the author*



***Figure 5.14:*** *Virtual Reality equipment testing, photo by the author*

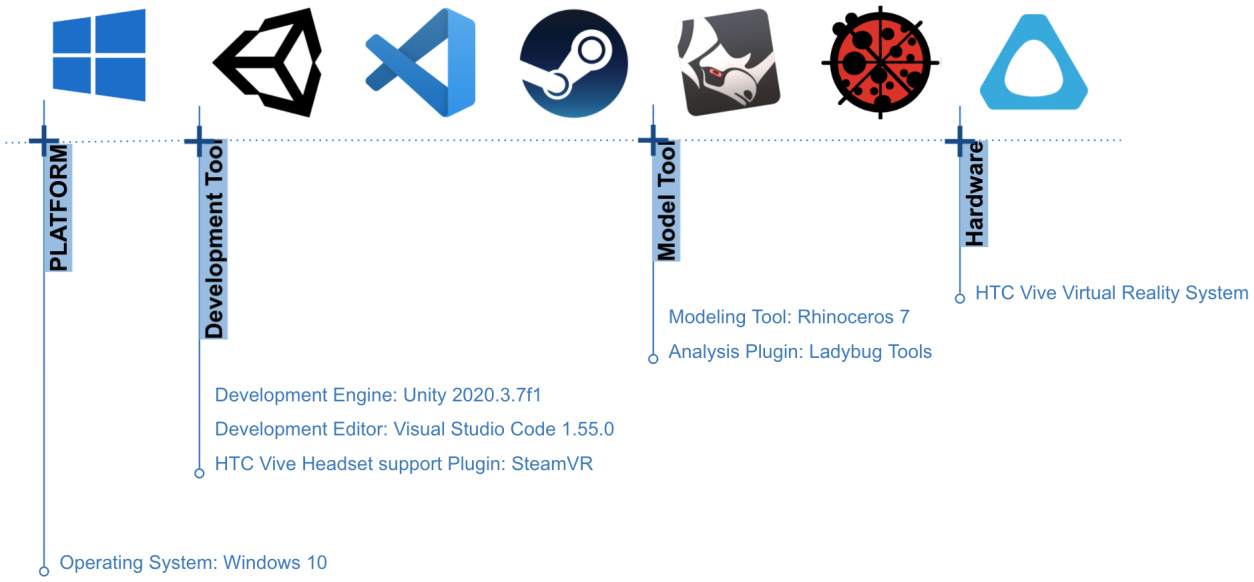



***Figure 5.15:*** *Software Overview, drawn by the author*

development using MacOS systems. Windows is much more mature in topics such as modelling, augmented reality and virtual reality.

- Unity 2020.3.7f1

  Unity provides a platform working as a cross-disciplinary game engine and supports modelling, lighting, rendering and customized actions controlled by scripts. The platform is able to host desktop and mobile game, 2D and 3D application, Augmented Reality and Virtual Reality developments. Unity also contains a hub with a bunch of plugins developed by versatile professionals for different use and tutorials which makes it even more friendly for beginners and amateurs.

- Visual Studio Code 1.55.0

  This lightweight script editor is connected with Unity and serves as the editor to manipulate C scripts related to Unity environment settings, shaders and colours, and customized Virtual Reality handler actions.

- SteamVR 1.20

  SteamVR can be interpreted as a plugin developed by Valve which connects Virtual Reality system and Unity or other gaming engine platform together and it becomes prominent for Virtual Reality gaming or applications.

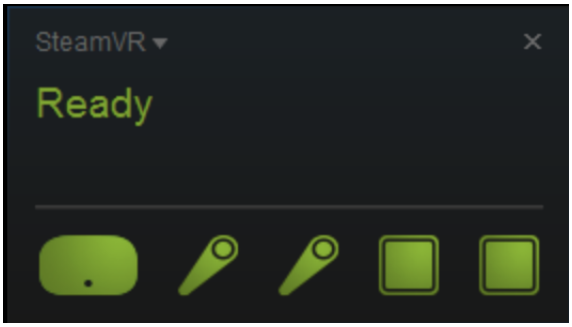



***Figure 5.16:*** *SteamVR running status, screenshot by the author*

- Rhinoceros 7

  Rhinoceros is a widely used modelling tools developed by McNeel. This modelling tool

is utilized to update the target model in real time for thermal analysis by Ladybug Tools with the same pace of the one in Unity.

- Ladybug Tools

  Ladybug Tools serve as the engine of thermal calculation in this research project. It is chosen due to its fast calculation, appropriate accuracy and abundant customization choices.

## 5.8 Experiment and Results

This section talks about the experiment carried out to evaluate the prototyping system and the corresponding results.

### 5.8.1 Experiment

An experiment is designed for the evaluation of the thermal engine system. Due to the continuing development of the pandemic, the user involvement has been restricted to limited scale. Five architectural students are invited to test the system with their own urban residence design. They were asked to either use their early stage models or create their draft model inside the system during the experiment.

A survey was designed to summarize testing information, user experience and feedback (Appendix 7.1). Their basic project information and testing screenshots are as follows. An overall analysis and evaluation will be provided in the results section.

1). User A
Site location: Chicago, IL, US
Site Dimension: 54m x 58m

Create or Import Model: Import

Testing Exception: No

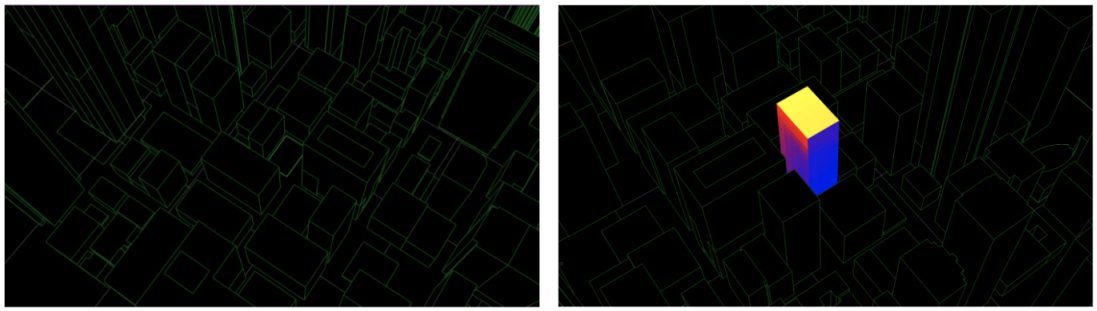


***Figure 5.17:*** *Site and sunlight visualization of User A, screenshot by the author*

User A chose to import an existing project located in Chicago to the system. The most important thermal related factor that user A values is radiance. So they set the visualization parameter to "Radiance", the duration to one year and the date to the most recent available data file. The result of sunlight visualization is good as their expectation with no buggy details and error. They can also successfully change the granularity of the visualization. They found they never know how bad the side of building with blue sunlight visualization until they directly entered the virtual system to experience it and decided to change the cube to a prism to improve the sunlight effects. User A also tried the "Humidity" visualization provided by the system but everywhere inside the block area was in a single color due to there were no large difference between each side of the cube.

2). User B

Site location: Shanghai, China

Site Dimension: 76m x 30m

Create or Import Model: Create

Testing Exception: Crash when changing to cubic MRT visualization.

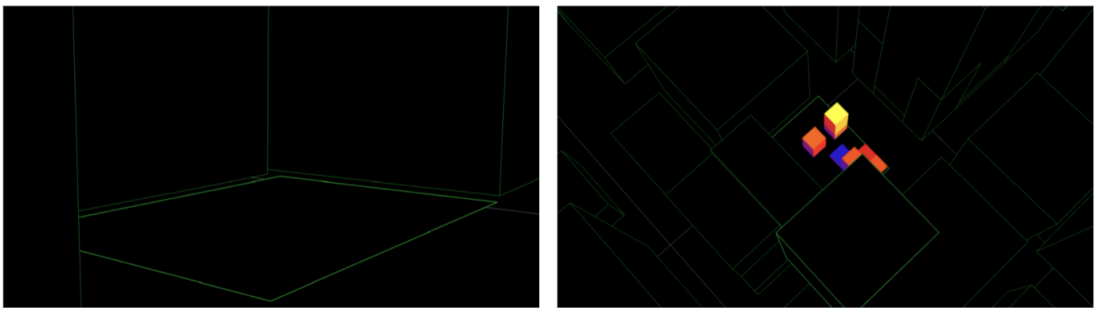


***Figure 5.18:*** *User B creating the design model, screenshot by the author*

User B has an ongoing project in Shanghai so they decided to create a design model inside the system. They first imported the site model and entered the virtual environment. They walked around for a while before starting creation and the feedback is if it is impossible to visit the site in person, a virtual experience is a relatively good alternative to feel the site before doing real design. Afterwards they created small cubes inside the site and chose the "Mean Radiant Temperature" visualization. They said the effect was reasonable and wanted to do direct model modification inside the virtual reality. They found the scale operation of cubes a little bit difficult to use because they had to move their hand far away physically to achieve a desired scale. But when they tried to change to cubic MRT visualization, the system crashed. In addition, user B experienced their design in both aerial and human being angles. Their advice was that in the human being angle, the colors were too sharp and it could be more gentle and encrypt more information.

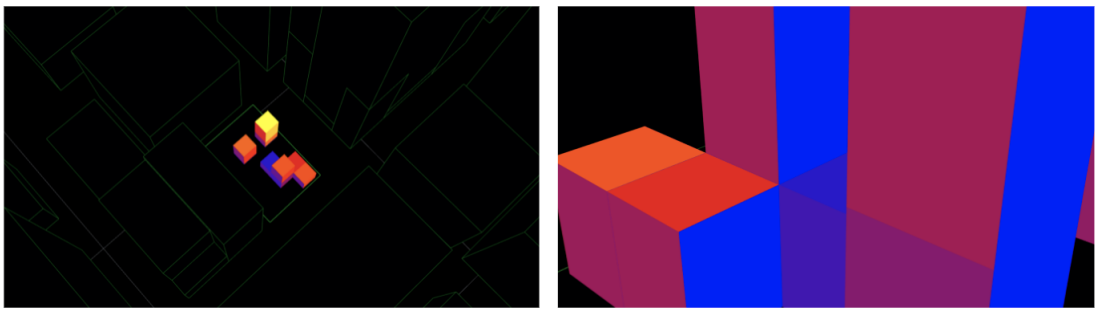


***Figure 5.19:*** *User B viewing visualization results, screenshot by the author*

3). User C

Site location: Tokyo, Japan

Site Dimension: 4m x 10m

Create or Import Model: Import

Testing Exception: No

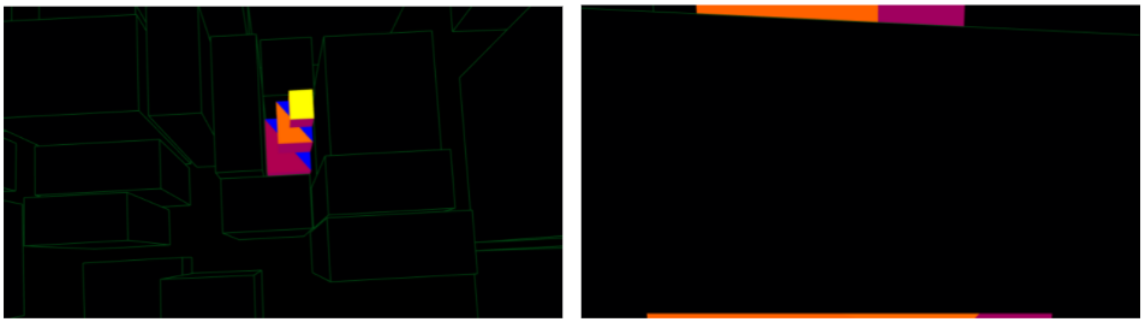


***Figure 5.20:*** *The result of user C from aerial view; Human eye view got occluded by buildings around.*

User C brought a design model with a site in Tokyo. The process was successful. However, due to the extreme compact urban condition of Tokyo, only aerial view can be successfully experienced and in the human being angle all the visualization were occluded by other building block models.

4). User D

Site location: New York City, NY, US

Dimension: 12m x 15m

Create or Import Model: Import

Testing Exception: Failed due to the imported model was too large.

User D had a real large scale model of half of the Manhattan island and the program directly failed during the model import procedure.

5). User E

Site location: Hong Kong, China

Site Dimension: 5m x 18m

Create or Import Model: Import

Testing Exception: No

The experience of user E is similar to user A only with a smaller site in Hong Kong.

### 5.8.2 Results

After finishing the experiment and the survey, five detailed data points are collected regarding this prototyping system.

All the projects are located in compact urban area and the dimension varies from $40m^2$ to $3132m^2$.

Among all the architectural students, only 1/5 has experienced Virtual Reality game before, while other 4/5 know VR but have never got chance to try it.

3/5 have considered sunlight and shading issues during earl stage of the design project but nobody have gone further with thermal analysis. 4/5 of them felt the thermal analysis results reasonable but 4/5 thought the system running a little bit slow and two people encountered crash because of extremely large model file and change of visualization data type. 2/5 said the user interface is cool but lacking in information in the visualization scene with a lot of information represented in the status and operation bar.

All of them indicated that the interaction was acceptable but not good enough for common use. 3/5 of them expressed interests in this VR-based application and thought the experience is totally different with original analysis tools that they have to watch the results via 2D

screen and the measurement of distance could sometimes be easily lost while virtual reality provides a 3D and real-scale experience to view their design with visualized thermal analysis results, also the system makes it easier for one of them to identify the critical area that affects the thermal comfort.

In general, 3/5 felt the system is effective as a proof of concept, and 2 of the students suggested improvements on the stability and computing performance of the application. There are additional comments on choosing other visualization approaches instead of only colors.

# 6 Conclusion

This chapter concludes the thesis discussion as contributions to the existing building analysis tools and the architectural and building industry, existed limitations found by the experiment and results, and future steps for improvements and suggestions to avoid unnecessary mistakes.

In general, the research question is answered that, experimentally, Virtual Reality and existing thermal analysis tools have the potential to be successfully combined to provide interactive and immersive thermal data visualization experiences for professionals to utilize in early stage of urban design.

For the aforementioned four sub questions, here are the findings and answers in summary with the detailed answers are mainly encrypted in the methods chapter. first of all, thermal data can be classified into several categories as heat, humidity and mean radiant temperature to be visualized in the form of color and cubes. With the adjustments of time, duration and granularity, effective visualization results can be generated. Secondly, due to the extreme professional requirements of thermal analysis tools, it is more reasonable to utilize existing tools, especially those open-sourced ones like Ladybug Tools series. To the third one, a light-weight green wire frame interface with black background is designed to reflect the scientific and experimental nature of this system and to attract users. A left hand-triggered status bar is developed as the main operation interface for user to interact with the system with less effort which shows the model and location information and supports the tune of parameters and cube operations.

## 6.1 Contributions

As a proof of concept, this thesis project does verify that virtual reality and existing thermal analysis tools such as Ladybug Tools can be combined to provide thermal data visualization results including mean radiant temperature, radiance, and humidity, which are effective for early stage urban residential building design.

The prototyping system is implemented which is based on experiences from previous researchers' explorations of Virtual Reality, Unity3D and thermal analysis tools, and casts light on future improvements and other related developments.

From the previous experiments, the awareness of thermal comfort, which is at least not sufficient among architectural students, can be drawn and emphasized during the experience of thermal effects in the prototyping virtual environment. If thermal comfort issues can be largely addressed by architectural design instead of heavily usage of heating and cooling system, the global carbon emission can be reduced and the environment can be further preserved as current environmental issues faced by all human beings are becoming more and more severe.

## 6.2 Limitations

There is still a bunch of limitations of this thesis research.

### 6.2.1 System Development

First of all, the system is not well developed with drawbacks and issues such as robustness concern, performance problem and too much resource consumption due to lack of experience of developing a VR application from front-end user interface to back-end data process and requests.

Secondly, the requirements for the data interaction between Unity3D and thermal analysis tools are redundant and complicated. It is not a good idea to do the interaction between those two sides repeatedly. A better idea might be encrypting the thermal analysis core system inside the Unity project with the open-source thermal analysis tools such as Ladybug Python program instead of using Rhinoceros and Grasshopper as the medium.

### 6.2.2 Visualization

Although several choices have been provided for visualization like granularity, data types and duration, according to the experiment and user survey, the visualization results still not very satisfying especially when it comes to the color representations. It might be reasonable to visualize sunlight with different color gradients, but things are different for other data sets such as humidity and wind.

### 6.2.3 User interface and interaction

The user interface and interaction is a little bit buggy sometimes and some design decisions are not reasonable, such as the choice of color theme making the system look unprofessional, the scroll bar of some items are too long for user to choose desired item with the handler in the virtual environment, the status bar is not always stable, and so on. Although testing a lot of virtual reality applications previous to the interaction design, the truth is that a professional UI/UX designer is still necessary for appropriate user interface and interaction.

## 6.3 Future work

This prototyping system is a working proof of concept relative to the proposed hypothesis, and there remains great space for improvements and explorations. This section basically corresponds to the previous section of limitations.

- User interface and interaction

  User interface and interaction need to be re-designed to make them more straightforward and user-friendly. More information needs to be displayed in the scene instead of only bare wire frame models and visualization results.

- Visualization

  For model visualization, whether a cubic simplification is adequate to choose is worth exploring due to an increasing number of buildings in irregular shapes such as spheres benefiting from the advancement of building technology. Maybe it would be a good choice to add spheres and triangles as basic units. For data, visualization approaches should be richer such as using geometry to represent wind flow to avoid using color for every data type which might result in user having difficulty knowing what data type the visualization results are.

- System

  The system needs to be refactored and some assumptions made to make the prototyping easier to develop should be cancelled like the rounding of numeric values. In addition, there are open-source thermal analysis tools in the building industry such as Ladybug Tools, so these code can be directly imported and used in Unity3D instead of doing complicated data and operation interactions through the server and database.

- Experiments

  The user amount is far from enough for a system testing. More targeted user from both educational institutions, industry and market should be invited to evaluate the application in all aspects. For the testing projects, all the project sites in the previous experiment are rectangular, it may result in neglected issues with circular site borders, so more data points and diversity should be introduced to the experiments.

# 7 Appendix

## 7.1 Experiment feedback survey

Feedback Survey

1. Where is your project site?

2. What's the dimension of your site?

3. Have you ever considered doing thermal analysis in the early stage of this design?

4. Do you feel the thermal analysis result correct or reasonable?

5. How satisfied are you with the user interface and interaction?

6. How do you feel between this VR-based analysis application and original analysis tools?

7. Do you feel VR real-time simulation overall effective?

8. Other comments or thoughts?

Thank you very much for the evalutaion!

# References

American Society of Heating, R. and Engineers, A.-C. (1996). *1996 ASHRAE Handbook: Heating, Ventilating, and Air-conditioning Systems and Equipment*. American Society of heating, refrigerating and air-conditioning engineers.

Attia, S., Hensen, J., Beltran, L., and Herde, A. (2011). Selection criteria for building performance simulation tools: Contrasting architects' and engineers' needs. *Journal of Building Performance Simulation*, 5:1–15.

Bahar, Y. N., Landrieu, J., Pére, C., and Nicolle, C. (2014). Cad data workflow toward the thermal simulation and visualization in virtual reality. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 8(4):283–292.

Basbagill, J., Flager, F., Lepech, M., and Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, 60:81–92.

DOE-2 (2008). *DOE-2 User Guide*. James J Hirsch Associates, 12185 Presilla Rd, Santa Rosa Valley, CA 93012, US.

Ellis, M. and Mathews, E. (2001). A new simplified thermal design tool for architects. *Building and Environment*, 36:1009–1021.

Gehron, L., Chernick, A., Morse, C., Naumovski, S., and Ren, Z. (2019). Sound space.

Krakhofer, S. (2015). Augmented reality design decision support engine for the early building design stage.

Krakhofer, S. and Kaftan, M. (2015). Augmented reality design decision support engine for the early building design stage.

LadybugTools (2012). *Ladybug Tools*. 2993 Eskridge Rd, Fairfax, VA, US.

Mazuryk, T. and Gervautz, M. (1999). Virtual reality - history, applications, technology and future.

Mortarotti, G., Morganti, M., and Cecere, C. (2017). Thermal analysis and energy-efficient solutions to preserve listed building façades: The ina-casa building heritage. *Buildings*, 7(3).

Natephra, W. and Motamedi, A. (2019). Bim-based live sensor data visualization using virtual reality for monitoring indoor conditions.

Nicol, J. F., Humphreys, M., et al. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE transactions*, 104(1):991–1004.

Peeters, L., de Dear, R., Hensen, J., and D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, 86:772–780.

Processing (2001). *Processing User Guide*. Processing Fundation, 7 West 96th Street, New York, 10025, US.

Rowland, I. D., Howe, T. N., et al. (2001). *Vitruvius:'Ten books on architecture'*. Cambridge University Press.

Solemma-LLC (2020). *ClimateStudio User Guide*. 89 Wendell St Cambridge, MA, 02138-1963, US.

Srivastav, S., Lannon, S. C., Alexander, D. K., and Jones, P. J. (2009). A review and comparison of data visualization techniques used in building design and in building simulation.

Sully, N. (2009). Modern architecture and complaints about the weather, or, 'dear monsieur le corbusier, it is still raining in our garage....'. 12.

Tablada, A., De Troyer, F., Blocken, B., Carmeliet, J., and Verschure, H. (2009). On natural ventilation and thermal comfort in compact urban environments – the old havana case. *Building and Environment*, 44(9):1943–1958.

Transsolar (2017). *Trnsys 18 - TRNLizard*. Curiestrasse 2, 70563, Stuttgart, Germany.

van der Rohe, L. M., Johnson, P., and Friedman, A. T. (2014). People who live in glass houses: Edith farnsworth, ludwig mies van der rohe, and phillip johnson (1998). In *The People, Place, and Space Reader*, pages 241–245. Routledge.

Vesely, M. and Zeiler, W. (2014). Personalized conditioning and its impact on thermal comfort and energy performance – a review. *Renewable and Sustainable Energy Reviews*, 34:401–408.

Wang, Q. (2017). Haden: Using virtual reality as an expressive medium for spatial design. Master's thesis, Carnegie Mellon University School of Architecture, Pittsburgh, US.