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A VENTILATION ANALYSIS OF BRUCE GOFF'S BAVINGER HOUSE

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BY

Lee Fithian

Marjorie Callahan

Shideh Shadravan

Dedication

I am dedicating this thesis to my late mother, whom I love and miss dearly and who raised me to be a motivated individual who thinks for herself. I am also dedicating this to the family and friends who have encouraged me and pushed me to complete my master's degree.

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Abstract

Bruce Goff's Bavinger house was deemed a peculiar marvel during its early years after construction. Originally completed in 1955, the architectural style was considered far outside the box, unorthodox and unconventional. Due to its uniqueness in style and shape, many of the operational and strategic components of the house were overlooked in favor of viewing its odd structure. Goff proved to be thoroughly analytical and intentional down to the drafting of details on his sketches and with this being a glaring truth with his other designs, it leads to the question of just how intentional Bruce Goff was.

The Bavinger house was built in the shape of a Fibonacci spiral; a logarithmic result of a maintained growth factor that expands further for every quarter turn from the origin by a factor of phi. The spiral extends 96 feet long (Sayer) and was bolted to the ground using a recycled drill stem. With this mathematical occurrence being found in nature, it is no coincidence that Goff's use of organic architecture was heavily influenced by nature's elements. Not only was the house designed using fractal architecture, but it also pushed the limits of modern architecture by employing the use of resources and material from the surrounding area. Goff's intent with using local resources cultivated innovation and ingenuity within the group of individuals who helped construct the house. With no HVAC system installed within the house, Goff planned for the house to utilize natural ventilation. How exactly, was this to take place, is what this thesis will be exploring.

Wind direction, site position, structure shape and material all play a part in analyzing the methods of how the Bavinger house managed to sustain natural ventilation techniques. While it

would be much more effective to visit the site and employ tests and procedures to obtain more accurate results, this is now no longer possible. The Bavinger house was demolished in 2016; due to multiple structural issues, deterioration, weather damage and conflict between the owners and the University of Oklahoma, the house was inevitably condemned to destruction. Though this is a deeply unfortunate occurrence and loss of a historical piece of architecture, we can recreate and reconstruct the Bavinger house as a digital model to run in software meant to test wind speeds and air flow. This digital data can give an accurate account of how the Bavinger house handled wind infiltration and performed natural ventilation.

Keywords: Bavinger, intentional, Fibonacci spiral, logarithmic, natural ventilation, fractal architecture, digital model, software.

1. Introduction

The introduction section will further provide a summary of the origins of the Bavinger house, its site layout, software analytics, and methods of testing and internal components that assisted in the natural ventilation.

1.1 Significance of Utilizing Software

Architecture is deemed to be the intersection of art and science. It evokes creativity, encourages innovation and lends inspiration from history to designs of the future. A multitude of the world's greatest structures are still standing today; used as pinnacle teaching points when the study of architecture by students begins. The intricacies of many of these larger, historical structures is carefully dissected and given multiple hypotheses to explore and research.

Architects, mathematicians, engineers and scholars have all come together to craft explanations as to how, when and why many of these historical structures were created. As preservation efforts increase to maintain many of the world's most influential designs, many projects on a more localized scale, completed by regional and stateside architects throughout history, have been given far less attention. One notable architectural design that was lost- created by Bruce Goff as well- was his creation of the Shin'enKan house. The house was erected in Bartlesville, Oklahoma and was given the name "Shin'enKan", which stands for "The House of the Far Away Heart" (Meier 2016). The house was under construction for Joe Price from 1953 on into the 1970's (Summers 1996). With the original intention of the structure being a type of "bachelor pad", the quirky and whimsical interior design made sense in order to compliment the freedom of Price's architectural exploration at the time (Brown 2003). Once the structure was deeded to the University of Oklahoma (OU), the house was then proclaimed a Bartlesville landmark. It had immense detail such as an indoor pond with gold fish, exterior ponds around the site, a marble loft, plastic strips hanging from the ceiling like rain, goose feather accents, glass cullets, embedded onyx stones, glass accents, extensive plush, white carpeting with a lush texture, a living room pit in the shape of a hexagon and walls constructed of coal (Brown 2003). The house had a strong Japanese influence throughout; with characteristics of the culture engrained at every corner and mosaics that plastered the windows with colorful artwork. The cost to build the house was a substantial amount of money- 1.2 million to be exact- however, Bruce Goff still maintained his usage of spare and waste materials to complete the interior and exterior design. After the house was purchased from OU in the summer of 1996 by a group of Bartlesville individuals who were interested in restoring it, tragedy struck (Summers 1996). In late December of that same year, neighbors to the Shin'enKan house awoke to images of the structure ablaze outside their windows. The house had caught fire overnight, and by the time Bartlesville firefighters had reached its location, it had nearly completely burned to the ground. This of course was a highly unfortunate loss that left many individuals confused and saddened, as the cause of the fire was never fully concluded. The loss also caused a decrease of financial gain since tourists would no longer be visiting the landmark. Roughly 4,000 people came annually to visit the house, however that is no longer possible, and admirers are now left with only memories and photos of the masterpiece that once stood there. The house was lost far before newer advanced software's that are available in the 21st century could have monitored and improved the structural integrity.

Focus on building new structures in suburban and city landscapes has been streamlined; calling for the quick demolition of older structures and the immediate construction of newer, more modern architecture.

The methods and techniques used by many of these historic pieces have been discarded with the demolishment of the structure. In more recent years, the historical importance of many of these smaller town and city landscapes has been emphasized, and efforts to restore and remodel these designs have been employed. Inversely, it is still too late to physically study and examine many of these historical architecture pieces. In order to gain an understanding of these lost structures, new methods of software analysis are utilized and explored.

Esri CityEngine is an advanced 3D software that can be used to create large urban sites and environments (Esri). The data used within CityEngine comes from actual, GIS information, and it assists in constructing architectural environments from past and present areas. This software is used to map city that have been long gone, as well as cities that are currently under development.

Bentley, a software company that produces programs that can be utilized in constructing urban and suburban landscapes, provides a plethora of design software that assists in the monitoring and creation of architecture. Components such as budget, weather, temperature, location, and materials are just a few of the variables Bentley uses to construct the most accurate of designs. A few of the software that have been released by Bentley are GenerativeComponents, a Revit plugin called I-model, OpenBuildings and Hevacomp (Bentley). These software's eliminate further errors that could be caused by human negligence and it works to uncover hidden components from historical architecture designs that have since been long gone.

Autodesk, a heavy contributor to the research done on the Bavinger house, employs a variety of software that can help any architect or student to completely understand their designs or those of others. Autodesk works in tandem with all the software that is under its umbrella, to allow for a seamless transition from program to program. It also allows for files to be saved in varying formats for their implementation into internal and external design programs. The software company utilizes BIM technology along with dozens of compatibility components that can help when switching software providers (Autodesk). Students and professionals have access to this software and it is being used in the present moment to create some of the biggest and most efficient of structures. In the case of researching and testing a 3D model of the Bavinger house, Autodesk software has been used the most out of any advanced programs listed and not listed. A few of the programs Autodesk offers are, 3DSMax, Autodesk Flow, a partial computational fluid dynamic program (CFD) program, Revit, and Navisworks. There is an array of programs provided by Autodesk that can produce the design and research results that architects, engineers and students are looking for.

Advanced software can give a more accurate understanding of the geometry and structure of these lost designs and can also identify how the architectural layout and construction aided in heating, cooling and ventilating the structure.

1.2 Additional Lost Architecture

Another example of a lost architectural landmark with historical significance in North America, was the Mecca Flats residential building located in Chicago, Illinois designed by Mies van der Rohe. The housing unit was constructed by Edbrooke and Burnham in 1891 in response to rising agitations with traditional apartment living (Bluestone 1998). It housed 96 units and combined the luxury of an interior courtyard, with the benefit of holding multiple families. Rather than centralized stairways and elevators, access to each corridor was achieved by placing entrances at various locations within the courtyard and around the exterior of the building. This took congestion out of the typical central lobby, and it provided more exclusive access to the residents who resided closest to the respective stairwell. At the turn of the 20th century, an influx of African Americans moved into the Mecca Flats, and a new cultural significance was cultivated within the Mecca. The residence went on to inspire poems such as “In the Mecca” (Bluestone 1998), songs such as “Mecca Flat Blues”. Unfortunately, as the Chicago city landscape continued to change, pushback on maintaining and keeping the Mecca Flats standing became increasingly substantial. By the middle of the 1930’s, the Illinois Institute of Technology expressed concern with attracting faculty and students to their campus due to the large population of African American residents in the area. Residents fought for nearly 15 years until the current governor at the time, Dwight Green, officially vetoed the bill. This consequentially sealed the fate for the historical Mecca flats and was destroyed soon after (Bluestone 1998). All that is left of this great structure are plans, sketches and photos, which can only be studied and observed up to a point.

Other cases of lost architecture are the demolitions of twentieth century buildings such as the Prentice Women’s Hospital and Maternity Center and the Rachel Raymond house. The Prentice Women’s Hospital and Maternity Center was first constructed in 1975 (Stott 2018). This building was also located in Chicago, Illinois along with the Mecca Flats. Bertrand Goldberg was the architect who created the structure. Goldberg’s form of architecture was often cultivated under Brutalism- which is the design of architecture in a raw and unaltered form. The design of the hospital incorporated crisscross hallways and lobby entrances. The exterior shape of the building was solely determined by the interior design and layout, thus, a shape akin to a four-leaf clover was created. This was the philosophy Goldberg used throughout many of his architecture creations. An interesting chance was taken by Goldberg at the time in order to complete his vision for this design, and he himself employed software devised data that allowed him to fulfill the structural need for load bearing walls. Rather than erecting external load bearing walls, Goldberg’s use of the software allowed for him to cantilever the walls from the internal center and core of the structure. Unfortunately, the early use of software, the structure's complex and deliberate design and the historical significance of the building were not enough to stop demolition in 2013 (Stott 2018).

In the case of the Rachel Raymond house, it had first been constructed in 1931 by Eleanor Raymond; an early female pioneer of architecture (Levine, Murphy, Traynor, Willis 2018). Raymond was also one of the first architects to employ modernist design and methodology in North America. This house was made specifically for her sister who shared similar experimental design interests, and it had a heavy influence of European architectural style. The components of the house and its stylistic design proved to be a marvel among the more traditional architecture methods that were being employed at the time. It was designed in Belmont, Massachusetts, and it had a distinct shape that differed from the usual Victorian era houses (Bowen 2007). It utilized many geometric block shapes and had exterior rectilinear forms present throughout. The large windows were steel sashed and instead of pointed roofs, Raymond employed flat roofs on top of the entirety of the structure. Metal railings as well as well as aspects of ample natural lighting. The house was renovated and changed many times throughout its lifespan, and though it was deemed by some to have lost its original allure, it was still prized among architects and historians. Raymond's design predated the home crafted by architect Walter Gropius, which was located in Lincoln Massachusetts (Murphy 2018). Gropius's house had been proclaimed one of the first modernist designs in New England, which was at odds with the history of the Raymond house. Even today his house has been preserved and well protected, however the Raymond house was purchased by the Belmont Hill School, a private boy's school, in 2006 (Murphy 2018). Despite immense preservation efforts, the house was demolished. Sadly, only images of the house remain, and any opportunity to physically study the historical house has been lost forever.

1.3 Background of Research

The Bavinger house, designed by the University of Oklahoma's very own Bruce Goff, was once located in Norman, Oklahoma. This intricately crafted architecture piece created by Goff- who was arguably ahead of his time- was once marveled as an unconventional and unusual creation. The house is described as being a "return to nature" that balances on the fine line of futurism and fantasy (Davies 2004). Goff was described as a progressive architect who employed a type of architecture that was heavily influenced by natural elements. He used a multitude of geometric forms to create his designs. For the Bavinger house in particular, a spiral-like shape akin to the Fibonacci spiral was created. Goff employed the theory of the continuous present, which was evident in his Bavinger design.

The construction of the house began in 1950 for Gene and Nancy Bavinger- staff members at the University of Oklahoma. Standing at a height of 55 feet, the house spirals upwards towards the supporting rod in the middle (Zizzo 2009). The rock covering the entirety the house consisted of 200 tons of ironstone that was quarried from a mine within the state. Steel cables recycled from biplane braces extend onto the landscape around the house, helping to tether the structure to the ground (Joye 2007). Many of the windows inside the house were unconventional and extended like glass sheets between the roof and the wall. The interior of the Bavinger house was also constructed using a multitude of recycled material. Fish nets, lighting fixtures and unused stone are just a few of the items they managed to obtain for constructing the house. Large blue pieces of glass cullet are implemented into the interior design to enhance the aesthetic (LeMaire

2011). The suspended saucers within the interior serve as “rooms” or designated spaces for sleeping and lounging. With intent, Goff spaced the saucers incrementally along the staircase landings. The highest and last saucer, protruded like a projecting cylinder from the top of the house (Davies 2004).

With the help of students, Gene and Nancy themselves, as well as other volunteers, the house was completed at a cost substantially lower than a usual home in that time period. Additional costs for the construction were remedied with the charge of one dollar for admission to view the house and its site (Mid-century).

Nancy and Gene Bavinger lived in the house for nearly 50 years, and they raised their children in the house throughout that time. In its later years, the funding to upkeep renovation of the house struggled. There was a staunch effort in 2008 enacted by the nonprofit Bavinger House Corporation. (Norman Transcript 2008). Bob Bavinger, the son of Nancy and Gene Bavinger, was at first, behind these restoration efforts, however, as time passed, efforts ceased to make little headway. Though the house was still standing, it had needed even more restoration after the intense storm damage it received in 2011 (Meier 2012). Soon after, Bob Bavinger closed access to the house and its site. Amidst much speculation, it was slated that Bob Bavinger did not want the University of Oklahoma interfering with his restoration efforts (Meier 2012). The house was effectively demolished in 2016 with little warning, much to everyone’s surprise. With much left unanswered, efforts to rediscover elements of the Bavinger house have resurged.

1.4 Software Utilization

The software primarily used throughout the testing and analysis of the Bavinger house are as follows: Autodesk Flow, Autodesk Revit, Climate Consultant, Autodesk NavisWorks BIM 360, AutoCAD, Autodesk 360 and Microsoft Excel for data input.

Autodesk Flow is a simulation software that utilizes computer fluid dynamics (CFD) to run digital simulations (Tara 2014). A wind tunnel is used to show the effects of wind speed and flow on digital models created using design software. Autodesk flow focuses on subsonic flow. Subsonic flow is slower than the speed of sound and is primarily applicable to architectural, automotive and consumer components (AD 2015). Flow can only be adjusted by air speed and it only runs wind tunnel simulation- which removes it from the fully capable CFD category- however, its ability to recalibrate and solve problems quickly makes it a sufficient candidate for this research.

Revit was used to edit the 3D design model to some extent. This was utilized primarily in stripping certain mesh components from the full design to allow for wind flow to enter certain areas of the model.

Climate Consultant was used to gauge the approximate wind speed and direction during all 12 months of the year. This was used in conjunction with the site location and orientation to assess whether or not the flow of wind assisted in cooling the house during the summer and blocking colder winds during the fall and winter months.

Navisworks BIM 360 and AutoCAD were both utilized for the import and export of files into different forms. The original 3D model of the Bavinger House was not able to load into Revit until it was exported to a different format.

Autodesk 3DS Max uses a system of complex animation components to manipulate and create detailed designs. In regard to this research, this software was used to cute and manipulate the shape and sections of the Bavinger house. Due to the complexity of the 3D Bavinger model, certain components and sections of the house were distorted. This distortion did not prohibit the circulation observations that were needed to conduct this testing.

Microsoft Excel was used to compile and analyze the data obtained from Autodesk Flow. Since the data is largely quantitative, calculations and visual representations were necessary to understand the results of the research. The calculations done were primarily conversions of the wind speed from miles per hour (mph) to feet per second (fps).

1.5 Research Aim

The objective of this study is to determine if the Bavinger house design, site layout and construction methods were intentional for aiding in air cooling and ventilating the structure.

1.6 Objectives

1. To determine if the logarithmic spiral shape was intentional in influencing airflow into the house.

2. To assess the components of the structure that aided in ventilation (pond, landscape, mechanics of house, etc).

3. To identify if the site plan aided in maximizing ventilation and cooling through the house.
4. To assess the accuracy and reliability of the software's used to simulate air flow.

2. Literature Review

The objective of this study, as proposed in the introduction, is to explore the wind effects and ventilation processes of the Bavinger House. To further help with uncovering the complexities and methodologies of Goff, computer simulation software can be utilized. This chapter will further examine fractal architecture (Mirmoradi 2017), organic architecture, the background of Bruce Goff and lastly, his methodology of design.

2.1 Background of Bruce Goff

Goff routinely rejected conventional methods of architecture, while simultaneously treating each individual project as its own special task (Mead 1995). Goff, being self-taught in architecture, used a significant amount of geometry, unusual materials, and space to construct his intricate designs.

Goff began his career at the age of 12 as an apprentice at an architecture firm in Tulsa, Oklahoma (Horne 1998). He continued working at the firm throughout high school, while simultaneously continuing his self-study of architecture. During this time, he connected with a multitude of architects and designers of whom he was influenced by. Some of these architects, more specifically Wright and Sullivan, encouraged Goff to restrain from seeking collegiate architecture courses if he wanted to maintain the inventive and imaginative side of his architectural work (Saliga and Woolever 1996). This prompted Goff to go full time into architecture work right out of high school.

Goff then spent his time as an architect working in Chicago in the 1930's. He even had a stint in the Navy working in the construction battalion (Henderson 2018). Afterwards, Goff moved to California and practiced briefly before returning to Oklahoma to accept a position as a professor at the University of Oklahoma in 1947. Shortly after his return, he was appointed chair of the College of Architecture on the campus, and he maintained this position until 1955. His career at the University of Oklahoma earned the College of Architecture high acclaim, nationally. These were correspondingly the years that the Bavinger House was constructed as well.

Goff relocated three more times after his tenure at the University of Oklahoma ended in 1955. These cities were Bartlesville, Oklahoma, Kansas City, and lastly Tyler, Texas where he resided till his death in 1982 (Saliga and Woolever 1996).

Goff did not gain national attention and recognition like that of his mentor, Frank Lloyd Wright. Perhaps this was due to the difference in personalities of the architects. Wright basked fully in his architectural praise much more than Goff had. Goff came off to be more about the work and the experience rather than the recognition. In fact, his mark in the field of architecture has been greatly debated throughout the years. Many argue that Goff's lasting imprint was not historical but was reminiscent of a time of extreme experimentation (DeLong 1976). His ideas and approach to architecture were labeled as "The Project Style", which deems that each design had its own unique problems with their own unique solutions (Horne 1998).

2.2 Fractal Architecture

The Bavinger house, along with many other of Goff's designs, is a very unique piece of architecture. Though many of his designs were not actually built, the drawings and plans that were creations of Goff have been archived in many areas around the US, namely at the Art Institute of Chicago and at the University of Oklahoma.

Bruce Goff was found to consistently utilize numerous geometries and patterns found in nature to cultivate his architecture. He heavily studied the works of Frank Lloyd Wright, who himself was labeled as the father of organic architecture.

Organic Architecture was coined by Frank Lloyd Wright during his time as a practicing architect in the early twentieth century. This type of architecture integrates the environment into the design and further supports the belief that form, and function are in fact one (Craven). The goal of organic architecture is to mesh the built environment with the natural environment and blend external and internal spaces. Wright believed that every structure should grow from the environment it comes from and he felt as if every building should function as a type of organism that is cohesive to the environment (Guggenheim 2010). Incorporated into typical types of organic architecture is usually plants, natural colors such as browns, oranges and yellows, and ample windows or skylights that flooded the interior of each space with natural light. Bruce Goff's style of organic architecture was perhaps more influenced by nature and the elements of the environment than Wright's. They both, however, embraced the use of natural and new materials, methods and technology. Today's version of organic architecture is different than that of the twentieth century. The organic architecture of Bruce Goff and Frank Lloyd Wright used more geometric shapes and straight lines in comparison to the utilization of curves and wavy lines in today's modern society.

The natural patterns and schematics of geometric architecture are said to have a likely attraction to the human eye. Given the complexities and styles of Goff, his architectural style was labeled "Fractal Architecture" (Joye 2007).

Fractal architecture has in fact been around for quite some time, however, it's popularity and style became prominent during the mid-sixties through the late eighties (Ostwald 1999). In *Recognition of the role of nature in the formation of fractal architecture*, Mirmoradi introduces what is called a "strange attractor". This is an elemental method in which a designer develops wide-ranging forms from natural ones, thus expanding their design from those forms. Mirmoradi details that Bruce Goff's design technique on the Bavinger house uses a spiral shape that is recognized as a natural attractor. "The spiral trajectory provides movement and visual guidance to itself" (Mirmoradi 2017).

2.3 Natural Ventilation

The Bavinger house was filled with miniature ponds at the bottom level that housed live fish and aided in the support of plant growth. What is initially known from this information, is that these ponds aided in air cooling the house in some way. Bruce Goff utilized passive design in assisting with the natural ventilation through the house. Natural ventilation is a process that relies on wind and an effect described as the "chimney effect" to cool down a structure (Energy 2018). To achieve the "chimney effect" convection is utilized. Convection is the process of cool air entering at a low level, capturing heat and hot air as it rises, and dispersing it through an opening or window at a higher level. This process mimics the effects of a vacuum. A suction like effect is created which pulls more air from the lower level. In regard to the Bavinger house, the logarithmic spiral design provides an almost perfect condition for convection. Though the number of operable windows is questionable, it is evident that the house utilized some form of air cooling since it lacked an HVAC (heating, ventilation and air conditioning) system.

A multitude of factors can influence how natural ventilation is achieved, and these can be combined or enhanced to produce the best ventilation possible. Combined ventilation principles can either inhibit or prohibit the maximum efficiency of a structure, based on what techniques are applied. The Bavinger house had sat on a cleared piece of land that resided in the middle of a wooded area. The number of windbreaks- which are natural wind inhibitors- were few on the actual clearing. Aside from the woods that surrounded the clearing, no large hills or edifices obstructed the wind from reaching the house. It is assumed that Bruce Goff and the Bavingers worked to employ methods that avoided heat buildup within the house. These methods have been debated, and apart from the firsthand accounts of those who studied under Goff, and those who have visited the house, there is a lack of available information on these techniques. The ventilation intentionality put into the house by Goff is also unknown, however, Goff was a staunch believer in using natural and recycled methods. He also employed the same belief with using materials located close to the site, or materials that have been discarded.

Natural ventilation can be achieved in 3 primary ways. The first of these is by stack ventilation. Stack ventilation uses temperature as its main component (Windowmaster). In this process, hot air rises to the top of a building, which creates a slight vacuum that pulls cooler air from the windows on the ground. Windows on the roof are used to release the hotter air and thus the process is continued. This can be enhanced by opening the windows that sit in the direction of wind flow, which will allow for the windows placed on that side to work in tandem with the flow direction. The flowrate (Q) is proportional to the difference in temperature, the buoyant pressure and the effective area of the openings (Fries 2004). Site orientation has no effect on this ventilation process, however, the size and height of the structure effects the efficiency of the process. A neutral plane, which is the area of transition where the hot air rises and releases, is needed.

The next form of ventilation is called single sided ventilation. Single sided ventilation positions windows on one side of a room. This technique of ventilation implements pulse ventilation, which is when the windows are opened for a minimal amount of time to allow fresh air to replace the older air. This ventilation process is not the most suitable for colder climates, as low temperatures and higher wind speeds creates drafts.

The last type of ventilation technique that is used is called cross ventilation. Cross ventilation is performed when both sides of a room, or building, have windows (Windowmaster). The windows that are facing the direction that has the wind blowing creates a current that pulls air through the space. To control the amount of air coming into a space, the windows facing the air direction are not opened as much as the windows opposite the incoming wind. The positive and negative pressure of the wind at an opening is represented by the variable (C_w). This value is dependent upon the wind incident angle and the positions of a building in respect to its vertical and horizontal placement (MIT). This C_w number would thus give a proportional flowrate (Q) relative to the area of openings present.

2.4 Air Cooling

Bruce Goff used an array of different methods in cooling his architecture designs. Though many of his designs were not constructed, he drew countless plans that included natural methods to cool spaces. This was with the use of water gardens and ponds designed throughout the structure. One example of this is his design of the Crystal Chapel. Herb Greene, a former student of Goff's, writes that the chapel was never built, however Goff called for the inclusion of an extensive water garden for the enclosure (Greene 2003). The garden was to have retractable windows placed at the water's level that would be opened during hotter weather to allow for natural cooling. In line with natural ventilation, this air would be pulled into the building from the lower level and the water would cool the air as it passed over. This air is pulled up through a partial vacuum and would be further expelled through the higher levels of the structure. Goff also exemplified a deeper understanding of air cooling and natural ventilation processes in many of his other projects as well. The Ford house was built for the Albert Fords in 1949. The house was located in Aurora, Illinois and was just as equally startling as Goff's other designs. Its shape was that of a large domed center circle that was shaped and formed by large steel arches (Mcarch 2010). Goff chose this shape as he believed that a circle was an informal gathering around a friendly form (Nicolaides 1960). The house shared many similar material characteristics like that of the Bavinger house. It utilized coal walls, glass cullets, surplus navy ropes, and other types of material that would otherwise be considered waste. The Ford house had no windows, and since it also lacked a contemporary heating and cooling system, natural ventilation was the only way to cool the house. Goff achieved this feat by implementing an array of hinged louvres and ceiling vents (Mcarch 2010). Goff's design on the Murdock residence, which was located in Midwest City, Oklahoma. The house insinuated a return to rectilinear forms by Goff, however, it still maintained much of his traditional, peculiar characteristics and methods. His application of ventilation in this structure was implemented by connecting a glass strip to the wall which allowed for adequate lighting and air circulation.

2.5 Passive Heating and Cooling

Passive cooling had to be utilized in order for these ventilation processes to work properly. Passive heating and cooling consist of implementing air cooling, shading, site orientation, thermal mass and insulation to create an environment that allows for a non-mechanical (without the use of an HVAC system) way of cooling a space. The building and the occupants inside need to be cooled in order to reproduce positive passive results. Not only is it the least financially expensive way to ventilate a house, it is also the least impactful form of heating and cooling on the environment. Bruce Goff seemed to understand that these components could be combined to allow for the best possible ventilation. Many of his designs took advantage of their location and climate to assure a cool temperature in the hotter months and a warmer temperature in the colder months. This method consisted of including air movement, thermal mass, cooling breeze openings, shading and site orientation (YourHome 2013). The methodology of exploring and uncovering these heating and cooling techniques will be further explained and explored below.

3 Methodology

3.1 Hypothesis & Supporting Data Introduction

In order to study the ventilation processes of the Bavinger house, a 3D model was created. This 3D model was created using an FBX (Filmbox) format that was then duplicated into multiples, and each multiple was allocated a control component. Once the component was identified, each model was tested using a virtual wind tunnel. Since the house was destroyed, the use of software for testing the accuracy of the hypothesis was essential. These tests were conducted using the software called Autodesk Flow, which is a program that utilizes computer fluid dynamics (CFD) (Tara 2014). Using the controls, each 3D model was tested using different wind speeds to assess the flow of the wind throughout the house. As stated in the introduction section 1.6, the main objective of the research is to determine whether or not the shape and site plan of the Bavinger house aided in its natural ventilation and air cooling. To further assist in reaching an assumption on the hypothesis, the construction components and additions inside of the house were also investigated and enumerated. The type of data being analyzed is largely quantitative, therefore the addition of tables, figures and charts was heavily utilized in the understanding and processing of the data.

The method of data collection and testing was intended to produce largely quantitative results that could be analyzed and translated into graphs and figures. These would thus be used to compare and contrast the wind effects on the Bavinger House.

3.2 Control Components

Table 1 summarizes the order of investigation and control components that were utilized to fulfill the research objectives. The investigation of control number 1 will establish the measures enacted to support ventilation and circulation. The 3D model control variables assisted in allocating the wind patterns on the site during the software data collection.

Table 1- Order of Control Testing

Investigation Order	**Controls**
1	Site and Design
	3D Model Controls (Autodesk Flow Utilization)
2	Wind flow coming from South
3	Wind flow coming from North

3.3 Climate Consultant Data

Utilizing the software Climate Consultant, the highest and lowest wind speeds from each month of the year were taken from 2017 wind data. The direction at which these winds blew were similarly collected for data inclusion. The region of interest selected was the Norman- Oklahoma City area. The wind speed data was displayed using a wind wheel graphing chart that also included the temperatures during the time of day that the wind speed was the highest. Colors on the wind wheel correspond to the independent variables that make up the daily data collected for the month. The only variables that were utilized from the wheel for this study were the wind speeds represented by the orange colors on the interior, and the green and yellow colors on the exterior of those orange wind speeds [Figures 8-19]. Though the wind wheel correlated certain colors to temperature, these colors cannot translate over to the color correlation in Autodesk Flow.

The miles per hour (MPH) were further converted to feet per second (fps) to input into Autodesk Flow. [Table 2]

Table 2- Wind Speed Conversion. MPH to FPS.

Month	Highest Speed (MPH)	Speed (FPS)	Lowest Speed (MPH)	Speed (FPS)
January	25	36.67	20	29.33
February	30	44	25	36.67
March	35	51.33	35	51.33
April	35	51.33	31	45.47
May	28	41.07	21	30.80
June	26	38.13	23	33.73
July	28	41.07	27	39.60
August	23	33.73	22	32.27
September	30	44	22	32.27
October	30	44	30	44
November	32	46.93	30	44
December	32	46.93	27	39.60

3.5 Qualitative Research

3.5.1 Site and Design Investigation

The site investigation explores the layout of the design as well as the materials and construction methods used to erect the structure. The information collected to help in this assessment included:

- The direction of the house on the landscape
- The details of the landscape in regard to vegetation, natural wind breakers and other wind inhibitors within the site
- The design systems relevant to ventilation and heating and cooling
- The relative temperatures in the spring, fall, winter and summer seasons
- The humidity components corresponding to the site.

These components were detailed and allocated to where their support was best utilized in influencing the air cooling.

3.6 Quantitative Research

3.6.1 Autodesk Flow Utilization

The climate data and investigated controls 2 and 3 [Table 2] were input into Flow to test the wind speed and direction on the 3D Bavinger Model. The data collected using Flow was subject to software limitations including:

- Wind flow diameter restriction
- Unavailability of wind temperature data,
- Mesh size restraints (wind flow lines could not accurately flow through openings made in the FBX file)

3.6.2 Sectional Model Constraints

The 3D model was edited in Autodesk 3DS Max (2017), to exclude the large windows near the NW side of the house. Note, it is unclear whether or not the ability to open these windows was possible. For the purpose of this research, the hypothesis was tested using operable windows.

The starting point of the spiral model was placed facing north and the voxel (mesh) size was set at .5 inches. This was done in order to clearly view the flow lines going through the structure. The model was sliced in half, with elements of the house still intact, to allow for the flow through the house to be seen. The flow directions were logged and translated onto section images to show the possible paths of travel the air took to ventilate the interior.

3.6.3 Air Flow Behavior Investigation

A sectional cut of the Bavinger model was placed inside the wind tunnel with the goal of observing and documenting the effects of the wind flow on the interior spaces of the house. To further support the data presenting that the apex is facing north on the site, the model was tested with winds flowing from both the northern and the souths within Autodesk flow. These airflow behaviors were further compared and contrasted. The Bavinger model was aligned horizontally within the wind tunnel along the direction of the airflow. After the simulations were ran with the winds coming from the south, the model was rotated 180 degrees to simulate wind flow from the north. The information collected was used to establish rotation patterns after impact on the site and the structure.

3.7 Excluded Criteria

1. The direct pin point of the wind speeds at the exact site of where the Bavinger house used to reside were not available on the Climate Consultant software.
2. The data for the wind during the early years of the dwelling were not available.
3. The excluded variables of the Climate Consultant Wind Chart consisted of dew point, hours of sunshine, and time constraints relative to a 24-hour period.

4. Heating components of the house were discussed; however, the cooling techniques were the primary focus of this study.

4 Results

4.1 Site Investigation Findings

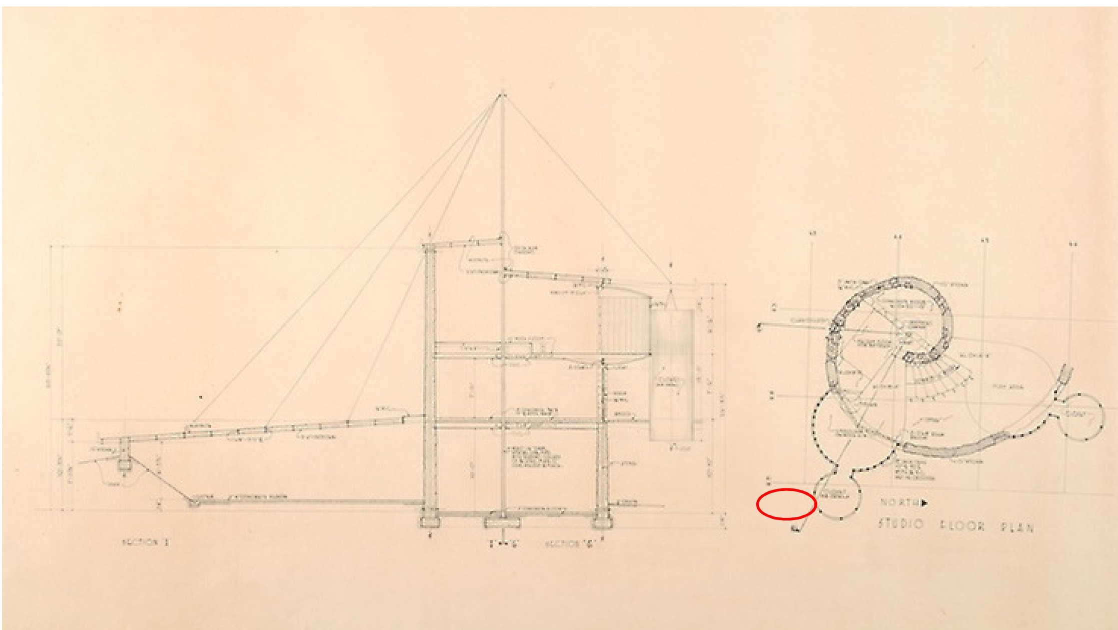


Figure 1- site plan with the apex of the house facing south. Image courtesy of Hidden Architecture.

One of the most significant findings with the design and site plan of the Bavinger house was that it was built 180 degrees opposite the drawn direction of some of the site plans. The apex of the house in fact faces north. This discovery was solidified by using aerial images of the site and comparing them with some of the plans made of the Bavinger house.

When searching for a site plan that was more visible, the orientation of the site continuously resurfaced with the apex facing south. This became an issue, as this would affect how the wind would circulate through the house during different seasons [Figure 1]. The wind on the site blows predominantly from the northern and west s. If the site would have been situated in this way, then strong winds blowing during the colder months would have routinely created colder climates on the interior of the house. This would have been very uncomfortable for the occupants, as avoiding the cold winds during the winter, and the high temperatures during the summer would have been a constant struggle. When another site plan orientation was discovered, Google Maps was utilized to pre-date the site before demolition, in order to view the correct orientation [Figure 3]. This means that from Goff's original drawings of the house, the actual constructed design was built with the tail end of the spiral facing south, rather than facing north. Out of the multiple site plan images that were compared, it was determined that this orientation, that has the tail end of the spiral facing the south, is in fact the correct orientation of the Bavinger house [Figure 2]. This was further cemented by the use of the Google Maps satellite images [Figure 3].

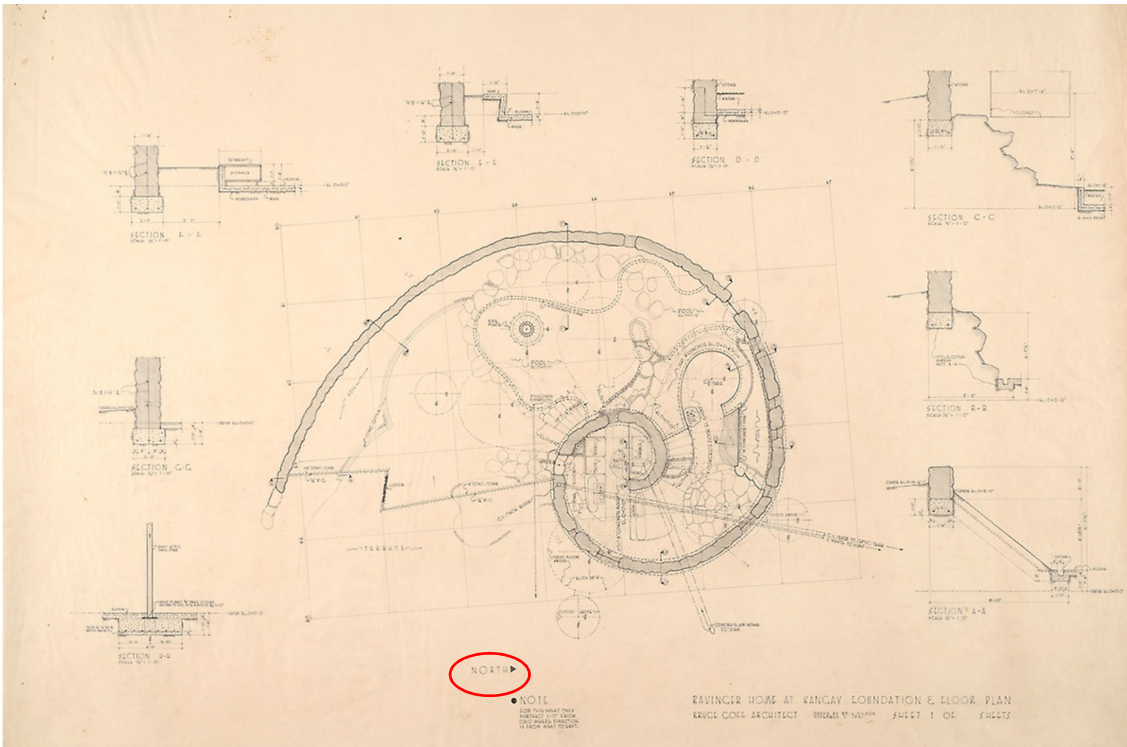


Figure 2- Site Plan oriented with apex facing north. Image provided by the Art Institute of Chicago.

Figure 3- Predated Google Maps Image showing the correct orientation of the Bavinger house. Courtesy of Google Maps.

4.1.2 Materials and Methods

The Bavinger house used a wide array of materials and methods that assisted in the heating and cooling of the house. These will be detailed below. Since the Oklahoma climate is fairly balanced between hot and cold temperatures throughout the year, Goff had to create a method of cooling and heating that would not be too overbearing in neither the hotter or colder months.

4.1.3 Thermal Mass

The first of these methods noted are his use of thermal mass materials. As noted in section 2-Literature Review, the Bavinger house used a large amount of quarried iron stone to complete the interior and exterior walls of the house. Stone often acts as a thermal mass, which is defined as the absorption of heat energy through a material (YourHome 2013). Stone typically has a high

Figure 4- Stone and Glass Cullets of the Bavinger House. Courtesy of ArchDaily.

thermal mass, and like its concrete and brick counterparts, it has the ability to store solar energy collected during the day and re-radiate it during the night.

Goff not only utilized the stone materials because of their resource location and aesthetics as shown in figure 4, but it appears his selection of material coincidentally works in tandem with the climate of Norman, Oklahoma. Since temperatures are rarely extreme through one particular season, the thermal mass of the stone likely increased

the comfortability of the occupants inside the house. This would have been highly beneficial during the winter and spring months. With the sun rising in the east and setting in the west, the site orientation would have enhanced the capturing of the solar energy during these seasons, and the thermal mass likely provided warmer internal temperatures during the nighttime.

During the summer and fall seasons, temperatures usually peak in the afternoon, and the sun shines for longer periods of time, as daylight savings time is not utilized during these periods. The orientation of the Bavinger house would have acted against these high temperatures by capturing less sunlight and heat on the west side when the sun begins to set. Thermal mass energy would have still been captured but was likely not enough to make the internal temperatures too uncomfortable, especially with the other passive cooling methods used in the house. It is important to note that thermal mass is not the same as insulation (YourHome 2013). Since the Bavinger house had little insulation, heat flowing through the house from the outside was likely not stopped or slowed by much.

4.1.4 Evaporation Ponds

The next contributor to keeping the Bavinger house cooled during hotter months was the implementation of the interior ponds located on the ground level. Goff described this internal area as a water garden. The water garden not only acted as a beautiful addition to the layout of the ground floor, but it also added to the whimsical nature of the Bavinger house.

Figure 5- Internal Sketch of the Bavinger house displaying the water garden location. Image Courtesy of Hidden Architecture.

The water garden was located on the northwest side of the house as seen in figure 5. Since the door of the Bavinger house was facing the southeast end, this placement of the water garden would allow for air to be cooled before rising into the upper levels of the house. Evaporative cooling is the process in which water evaporates and carries heat from the surrounding air (YourHome). This method of cooling the air works best in climates that have a relative humidity below 70 percent. In the case of Oklahoma, and more specifically the Norman / Oklahoma City area during the summer and fall months, the relative humidity is predominantly between 30 and 70 percent. This humidity range allows for the air passing over the water to increase the capacity of water vapor that is being captured. The Bavinger house utilized stacked ventilation. Stacked ventilation is the process of moving air up and through a building using pressure and temperature differences. Since hot air has a lower pressure than cold air, it moves up and is expelled through the top of the house. The humidity in the air creates the perfect conditions to allow for effective stack ventilation and evaporative cooling. The pods that served as rooms, were located above the pond in a step like, interval manner. The space below the pods would have carried cooler air up as it passed over the ponds and would have continued carried hotter air to the top of the house until this air was expelled through an outlet [Figure 6].

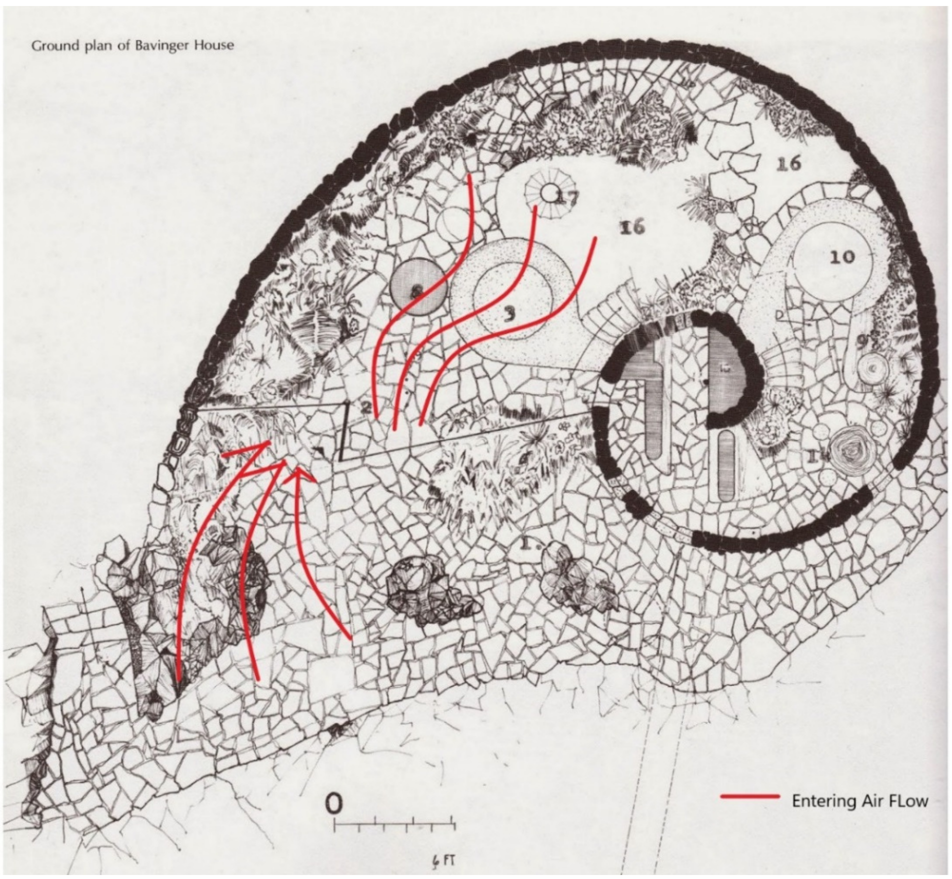


Figure 6- Ground Plan of the Bavinger house demonstrating air flow through the ground level. Image courtesy of Hidden Architecture.

Whether or not the pond was placed at that particular location for the purpose of air cooling is not fully known, however, it did assist in keeping the house cool due to the air moving over it.

4.2 Passive Cooling Principles

The Bavinger house satisfies a few principles of passive cooling in accordance with YourHome's guidelines (YourHome 2013). The required principles are listed as:

- Using roof spaces and outdoor living areas as buffer zones to limit heat gain
- Positioning windows and openings to enhance air movement and cross ventilation
- Choosing climate appropriate windows and glazing
- Installing and correctly positioning appropriate combinations of both reflective and bulk insulation
- Shading windows, solar exposed walls and roofs where possible
- Using and positioning thermal mass carefully to store coolness not unwanted heat
- Designing the floor plan and building form to respond to local climate and site

Out of this list, the Bavinger house satisfies the points labeled in table 3.

The house appeared to use the method of stacked ventilation, which was detailed in the previous section, 2.4 Natural Ventilation. The pathway the air flow moving through the house took, coincidentally had to move from the bottom to the top, as the shape of the Bavinger house mimicked an inverted vortex.

Table 3- Passive Cooling Principles met by the Bavinger House.

Passive Cooling Principles	Principles Satisfied
	Designing the floor plan and building form to respond to local climate and site
	Using and positioning thermal mass carefully to store coolness not unwanted heat
	Positioning windows and openings to enhance air movement and cross ventilation
	Shading windows, solar exposed walls and roofs where possible

For reiteration, the house has been destroyed, and is no longer physically standing. Thus, in order to maintain further accurate data, we have inserted the drawing into Autodesk flow to simulate wind effects on the house.

4.3 Wind Speeds

Using data from Climate Consultant (CC) visible in figures 8 through 19, the highest and lowest wind speeds were collected, with the highest speeds ranging from 15 to 35 miles per hour. These values can be observed in table 4 below. Wind speeds were typically higher and stronger from the northern direction, while speeds from the southern direction rarely surpassed the highest speeds for the north.

Winds coming from the east side proved to have the lowest wind speeds overall, with other low wind speeds varying in direction. The lowest wind speed collected was approximately 1 mile per hour. This wind speed was present at the start of one of the summer months, June.

Table 4- Highest and Lowest wind speeds and their incoming direction.

Month	Highest Wind Speed Direction	Speed (MPH)	Lowest Wind Speed Direction	Speed (MPH)
January	N	25	W	6
February	NW	30	W	6
March	SW	35	E	9
April	NW	35	E	8
May	NE	28	E	4
June	NE	26	NW	1
July	N	28	NW	2
August	N	23	NW	4
September	N	30	W	9
October	N	30	NE	6
November	N	32	E	6
December	N	27	E	7

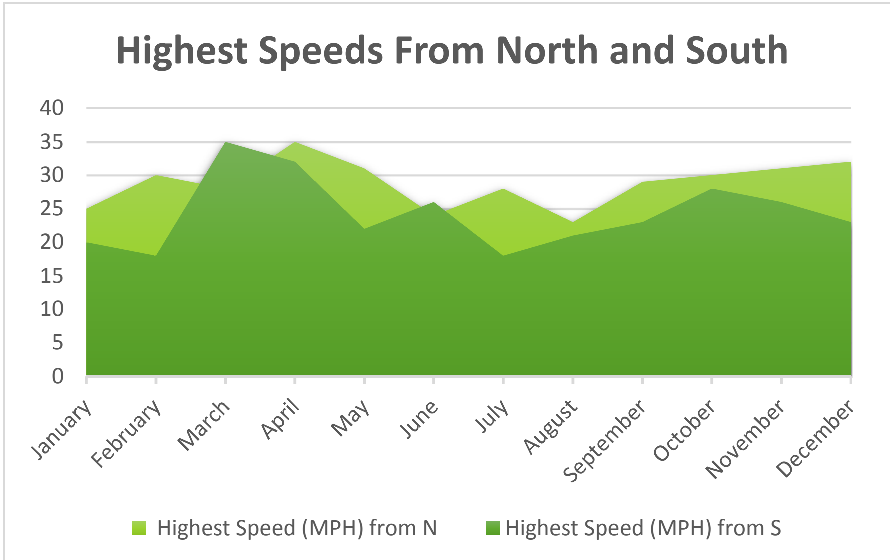
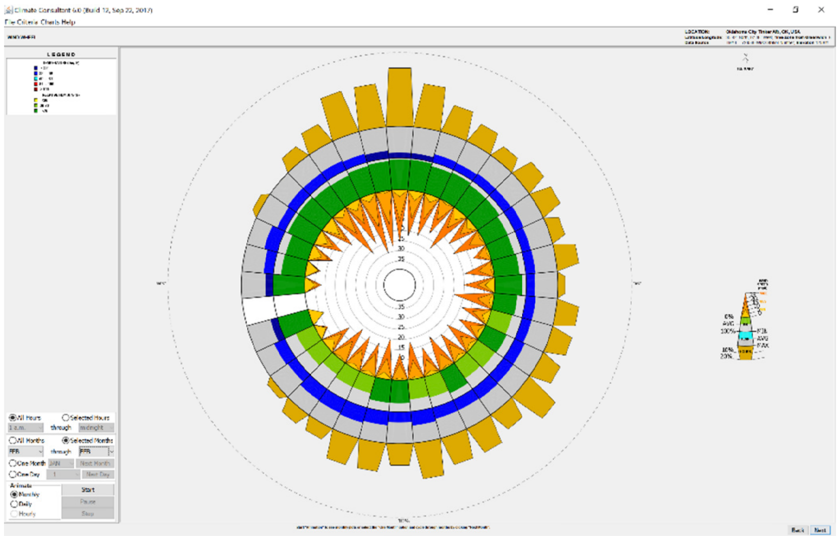


Figure 7- Wind speed behavior from the northern and souths.

Wind coming from the northern direction has a lower effect on the ventilation processes of the Bavinger house. The apex of the house is facing the north while the opposite end, closest to the entrance faces the south. With the winds coming primarily from the northern direction, majority of wind infiltration into the house during the winter months was prohibited.

Table 5 - Wind Speeds from the North and South Directions.

Months	Highest Speed (MPH) from N	Highest Speed (MPH) from S
January	25	20
February	30	18
March	28	35
April	35	32
May	31	22
June	24	26
July	28	18
August	23	21
September	29	23
October	30	28
November	31	26
December	32	23



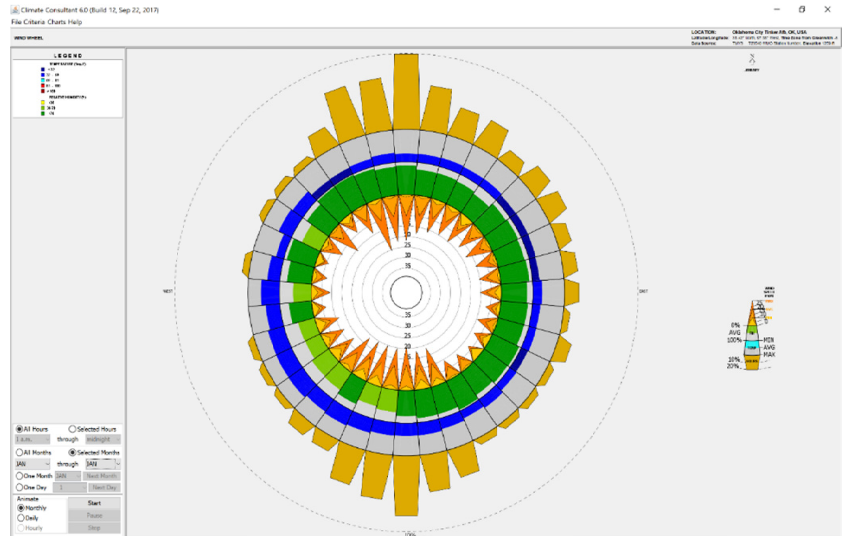


Figure 9

Figure 8, 9, 10, and 11- From Left to Right and Top to Bottom Climate Consultant weather data for Oklahoma City: Months of January, February, March, April.

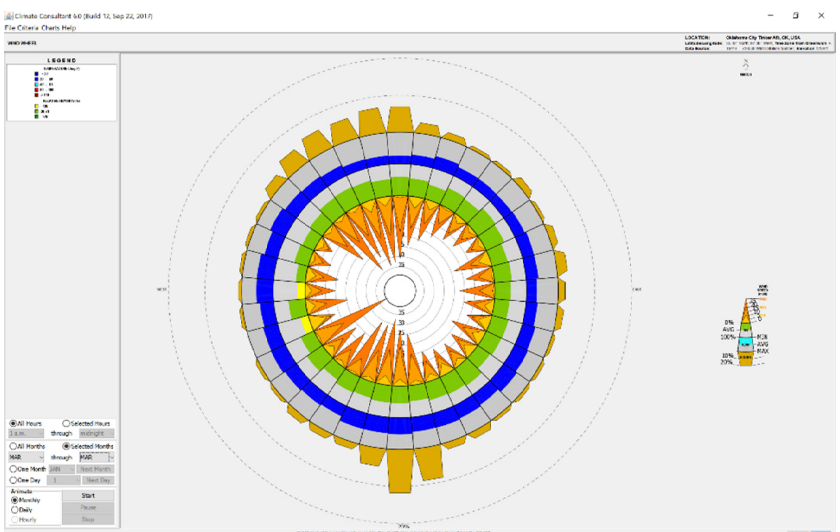


Figure 10

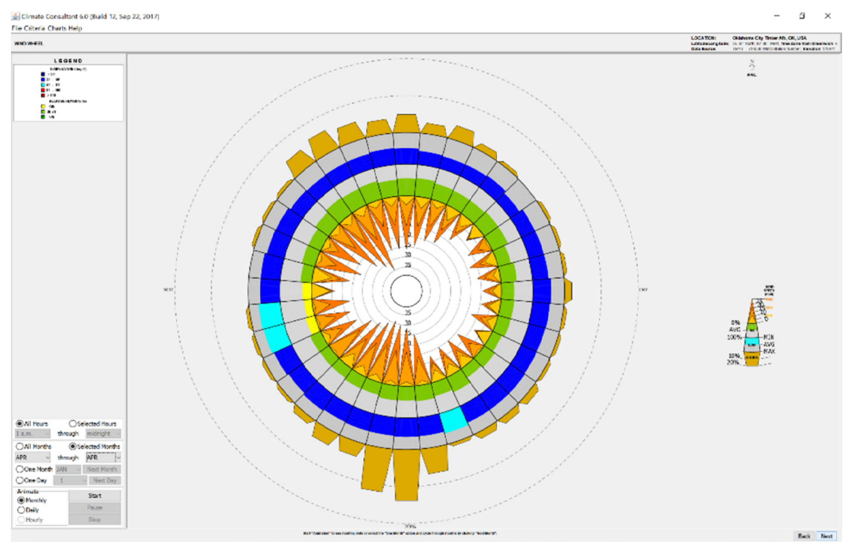
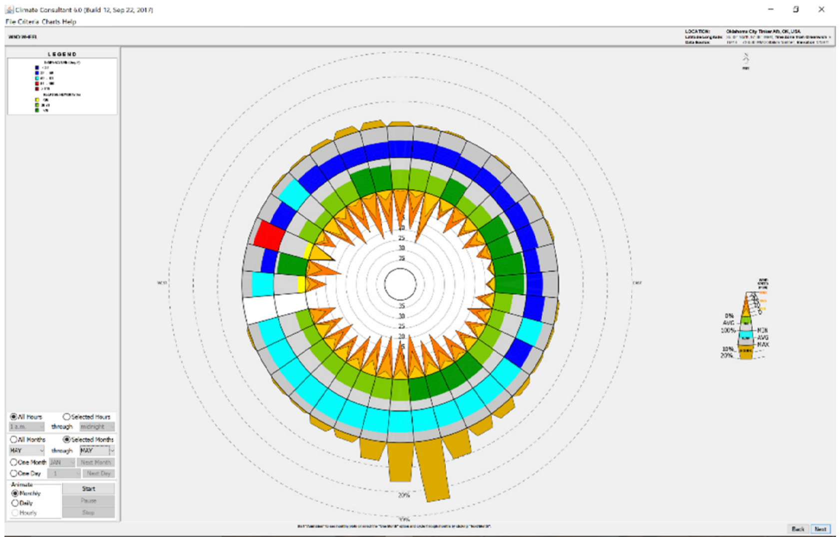


Figure 11



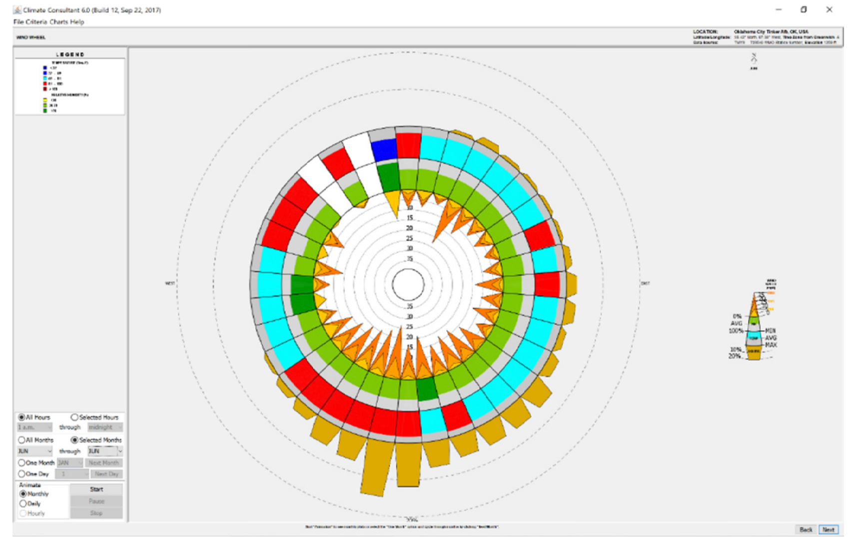


Figure 12, 13, 14 and, 15- From Left to Right and Top to Bottom Climate Consultant weather data for Oklahoma City: Months of May, June, July, and August.

Figure 13

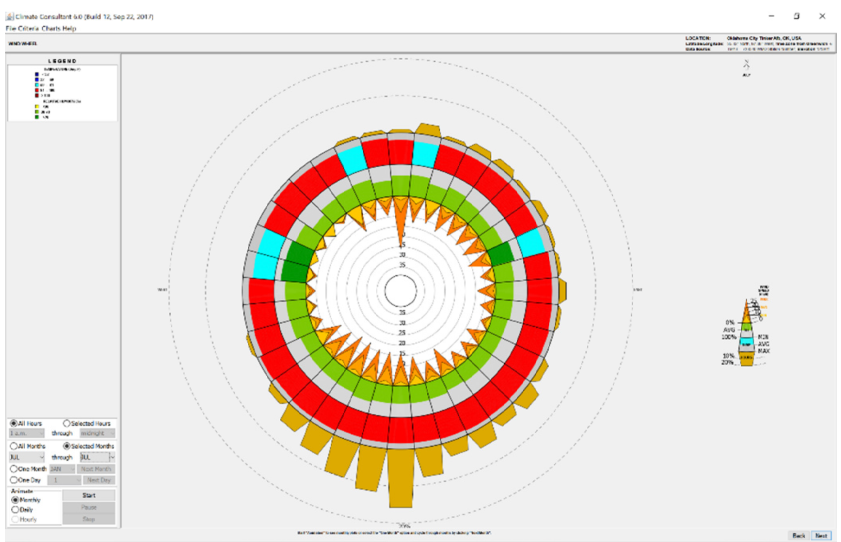


Figure14

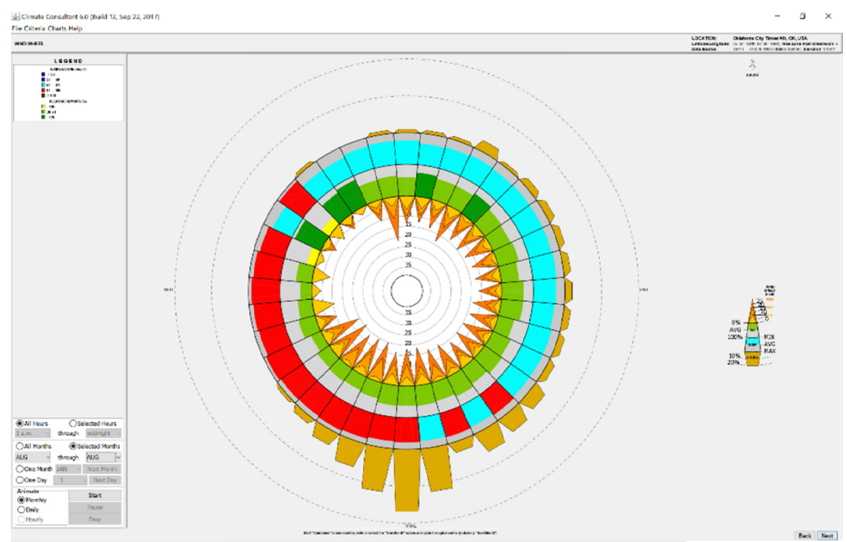
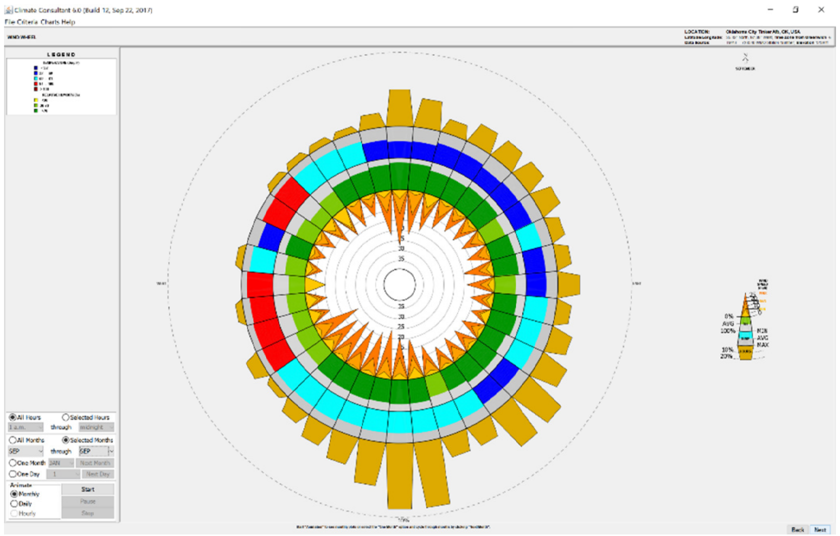


Figure 15



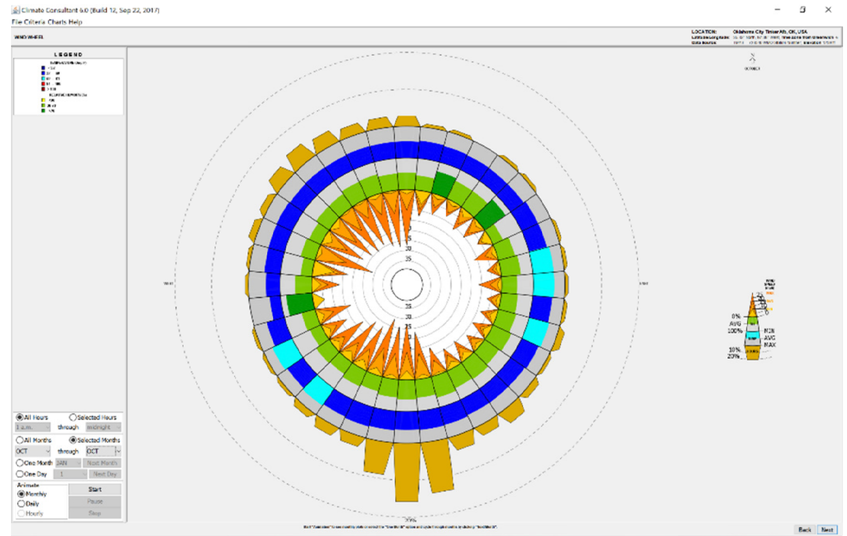


Figure17

Figure 16, 17, 18 and 19- From Left to Right and Top to Bottom Climate Consultant weather data for Oklahoma City: Months of September, October, November and December.

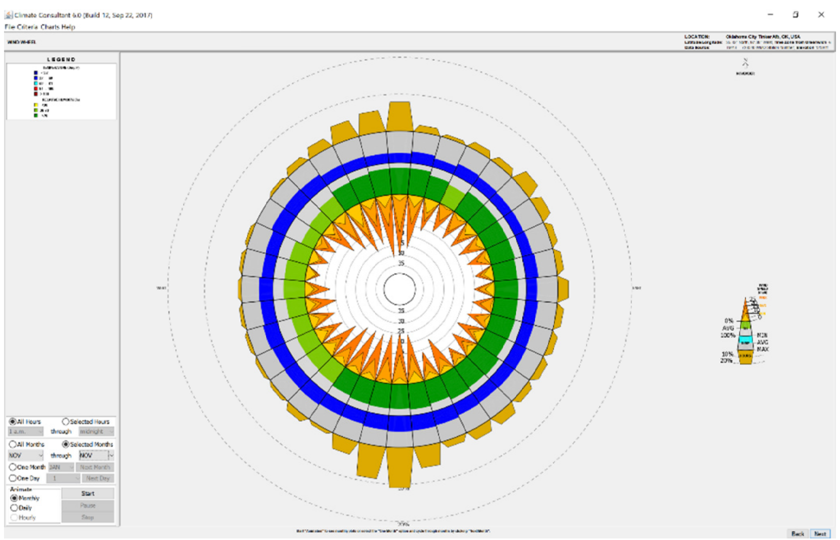


Figure18

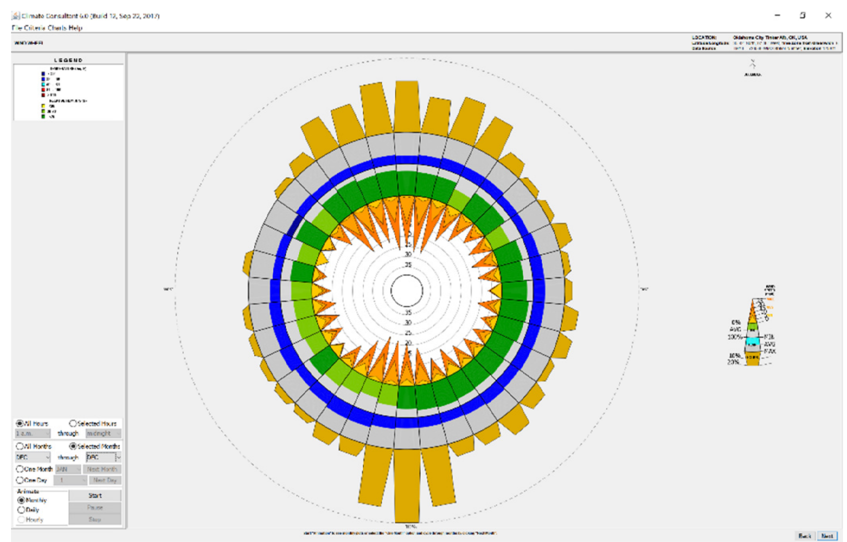


Figure19

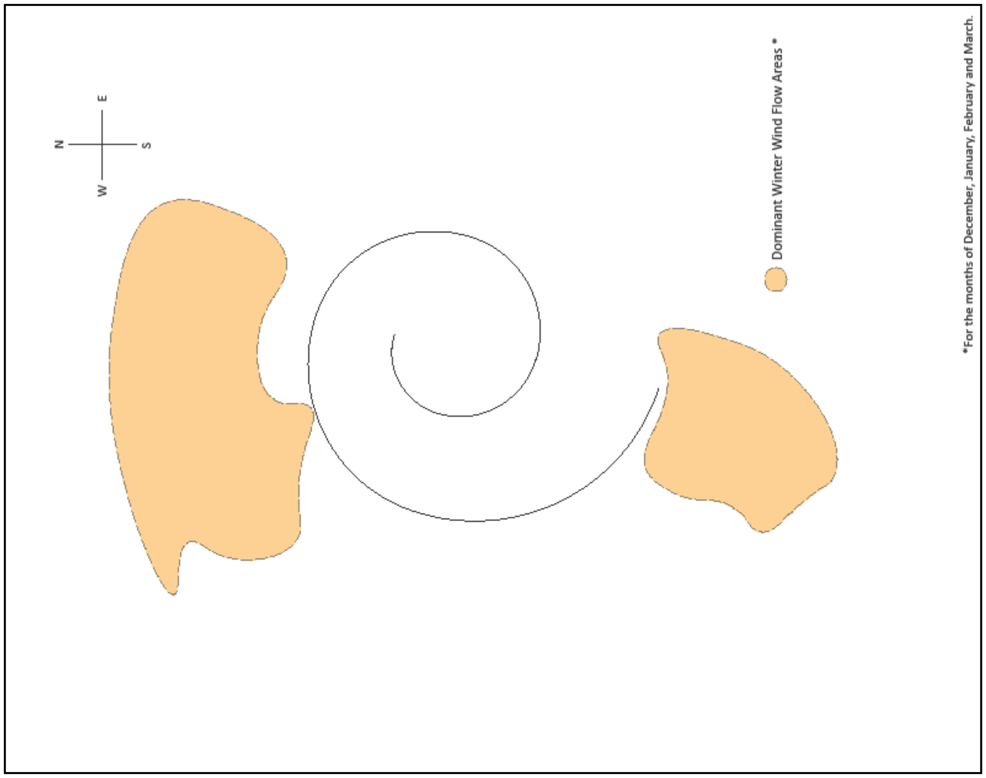


Figure 20- Primary Wind flow areas for the winter season.

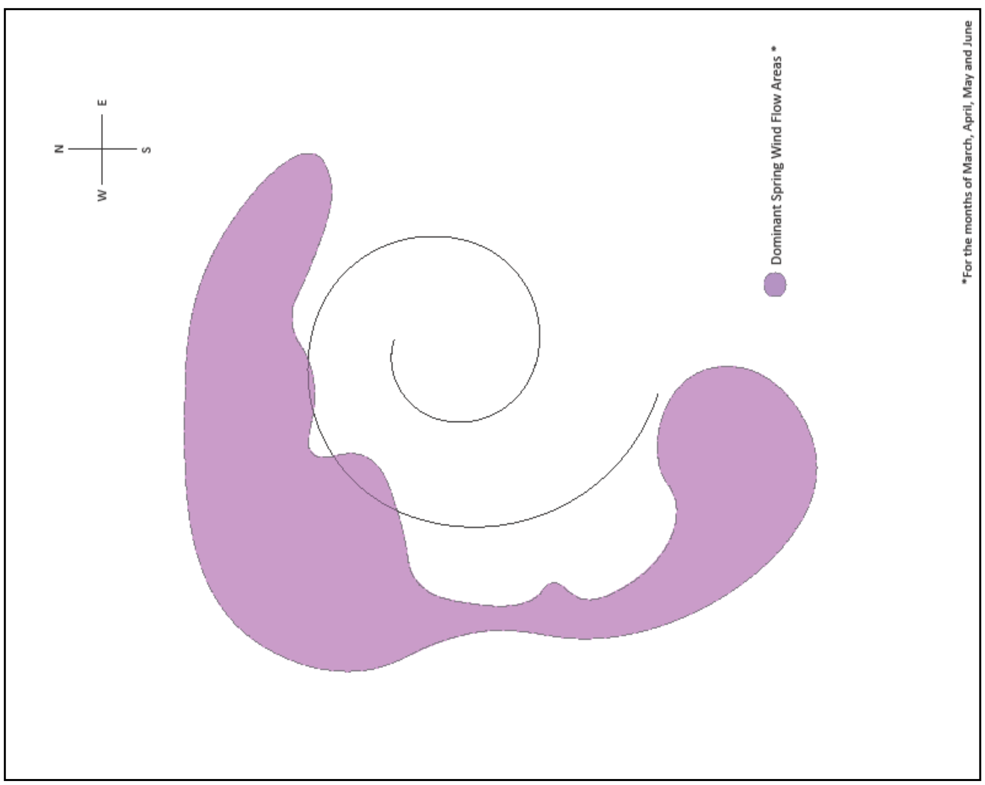


Figure 21- Primary Wind flow areas for the spring season.

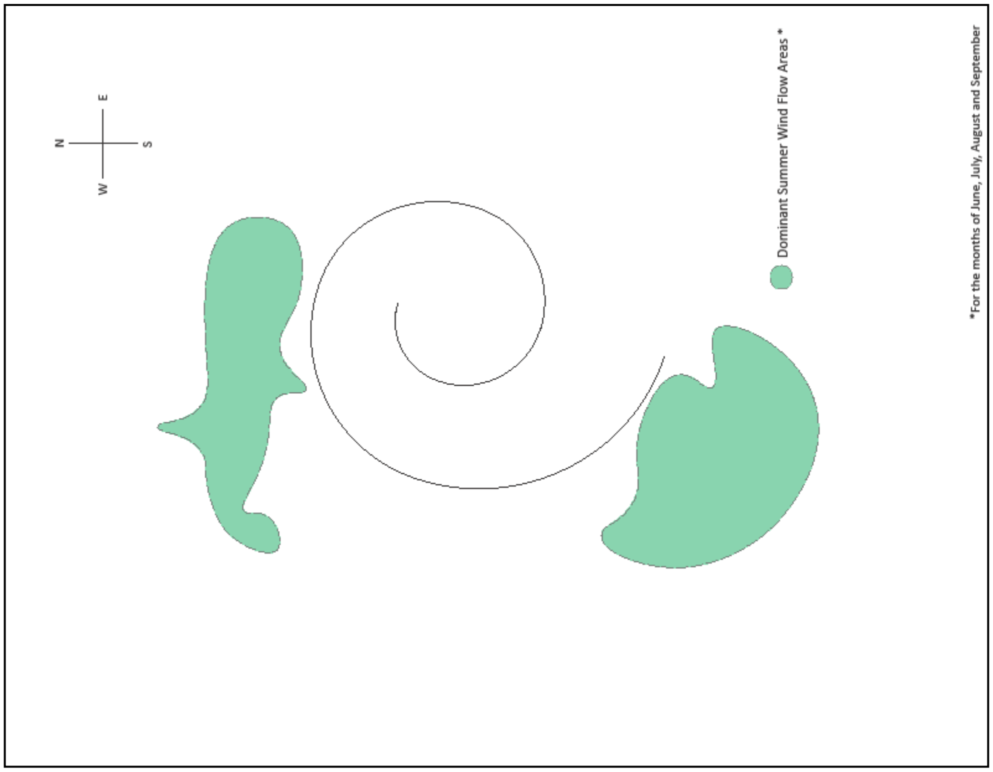


Figure 22- Primary Wind flow areas for the summer season.

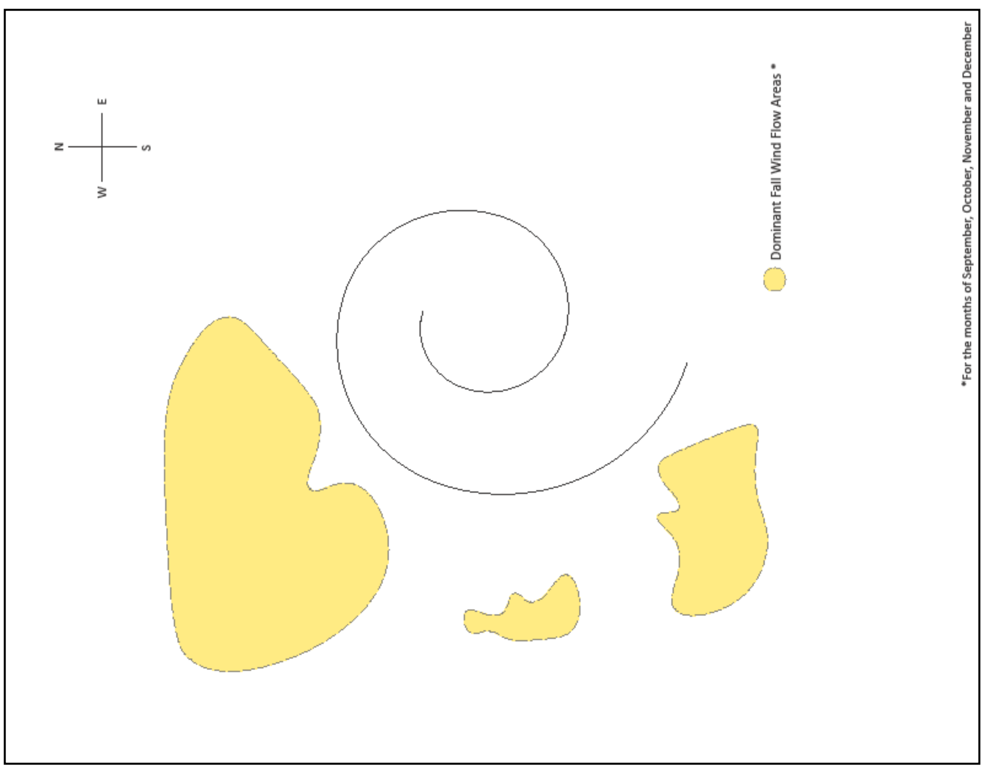


Figure 23- Primary Wind flow areas for the fall season

Figures 20-23 display diagrams showing the wind flow areas that correspond to the seasons. These diagrams were creating using the Climate Consultant wind data shown as the shades of orange in figures 8-19. It is apparent that most of the air flow comes from the north while the least amount of air flow comes from the south. This is the wind flow on the site, overall, without incorporating the structure. It is also apparent that during the spring months, the wind flow covers the most area in comparison to the other seasons.

4.3.1 Directional Analysis

The direction of the highest wind speeds during each month was documented as shown in table 6. This data was utilized in assessing which season had the highest influx of wind hitting the house. This was further utilized in gauging how much air would be taken into the house during the hotter months of the year.

The highest influx of wind flow was apparent during the months of March, April and October, with speeds reaching above or at 28 miles per hours (MPH). During the summer months, as allocated in table 4, air flow from the north reached peak speeds of 30 MPH. Speeds ranged between 20 and 30 miles per hour with wind flow coming from the north throughout majority of the season.

Table 6 - Highest wind speed and direction.

Month	Highest Wind Speed Direction	Speed (MPH)
January	N	25
February	N	30
March	SW	35
April	NW	35
May	NE	28
June	SW	26
July	N	28
August	N	23
September	N	30
October	N	30
November	N	32
December	NE	32

The seasons are allocated as shown in table 8. The hottest months of the year are from June to September in Oklahoma, while the coldest months of the year take place from December to March. Ventilation processes are most important during the summer time due to the hot temperatures reached. Table 8 also lists the corresponding humidity ranges for each season.

4.3.2 Spring Wind Flow

Wind flow during the spring season produced the highest wind speeds. During the spring in Oklahoma, rainfall is heavy, with most rains coming in during April and May. Temperatures begin to increase, however, wind speeds decrease towards the end of the spring season and the beginning of the summer season. Ventilation processes primarily had the largest effect during the spring, as the rain and wind speeds provide the most efficient air cooling conditions.

4.3.3 Summer Wind Flow

During the summer, wind speeds were at their lowest while temperature was at its highest. Ventilation processes would not yield results as efficient as the spring season, however, adequate wind flow can still be achieved due to the general amount of wind coming from the north. August had the lowest wind speeds with the top speed reaching 23 miles per hour. August also had the lowest wind speeds throughout all the seasons. Wind flow during these hotter months was overall low and reliance on other ventilation processes would have needed to be heavier without the assistance of either lower temperatures or stronger winds.

4.3.4 Fall Wind Flow

During the autumn season, wind flow was at the average speed of 30 during the entirety of each month. The direction of wind flow comes from the north for all fall months. The lowering seasonal temperatures as well as the influx of stronger winds provide adequate conditions for the air cooling the interior of the structure would have needed during this time.

Table 7- Temperature and Humidity data for Oklahoma.

High °F	Low °F	Month	Average Humidity Range %
50	29	January	30 to >70
55	33	February	>70
63	41	March	30 to 70
72	50	April	30 to 70
80	60	May	30 to >70
88	68	June	30 to >70
94	72	July	30 to 70
93	71	August	30 to 70
85	63	September	30 to 70
73	52	October	30 to 70
62	40	November	>70
51	31	December	>70

4.3.5 Winter Wind Flow

Wind speeds in the winter season increased overall each month until the spring. January is on average the coldest month of the year in Oklahoma according to Current Results weather records [Table 7]. January also has the second to lowest wind speeds of the entire calendar year based on the weather data collected from Climate Consultant. This positively correlates with the data that supports the hypothesis that the site placement of the Bavinger house was beneficial in blocking wind intake during the colder months.

Table 8- Data corresponding to the seasons and the humidity range throughout the year.

Seasons	Dates	Humidity Percentage (%)
	Winter	
December	Dec. 21st- March 20th	>70
January		
February		
March		
	Spring	
March	March 20th- June 21st	30 to 70
April		
May		
June		
	Summer	
June	June 21st- Sept. 22	30 to 70
July		
August		
September		
	Fall	
September	Sept. 22- Dec. 21st	30 to >70
October		
November		
December		

4.4 Wind Flow- South

The findings from the CFD software are detailed in the sections below. All wind flow characteristics pertain to flow coming from the south.

4.4.1 Flow Line Behavior

To reiterate, for investigation 2, the model is placed with the winds blowing from the south. This data goes against the hypothesis that the house was built with the apex facing north. In Autodesk flow, this is simulating how the winds would have infiltrated the interior spaces, had the apex of the Bavinger house been placed facing the south. The flow lines were oriented horizontally, parallel with the plane of the model. This placement allowed for the circulation impacts to be viewed from the northern and southern sides. The colors represented by the flow lines signify the speed at which the air is coming into the space. Dark blue and purple lines are seen, thus signifying a slower air speed verses the orange and red lines present on the exterior of the model. From figure 24, intense flow line circulation can be seen within the interior of the structure.

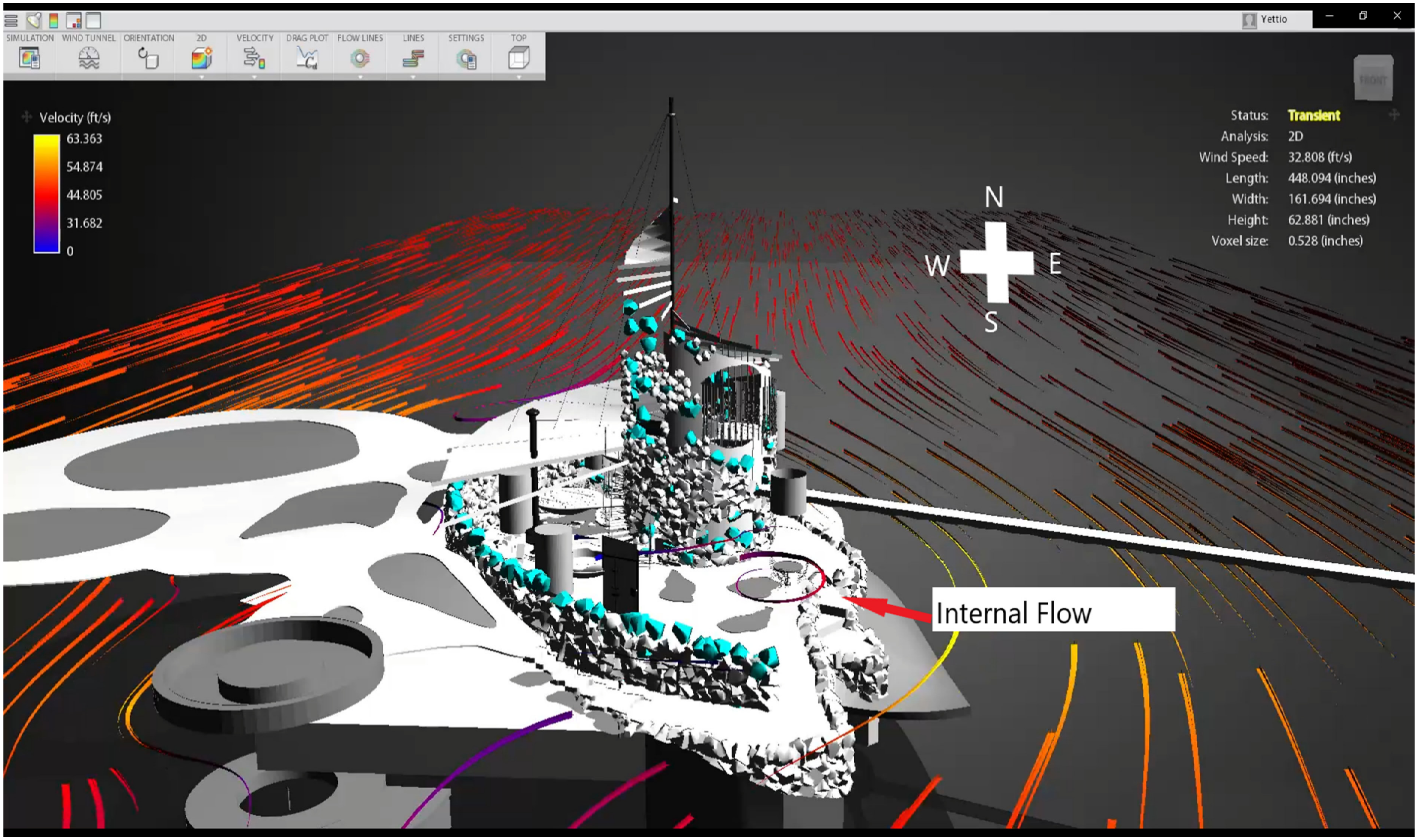


Figure 24- Section cut 3D model interior airflow behavior. Winds coming from the Southern .

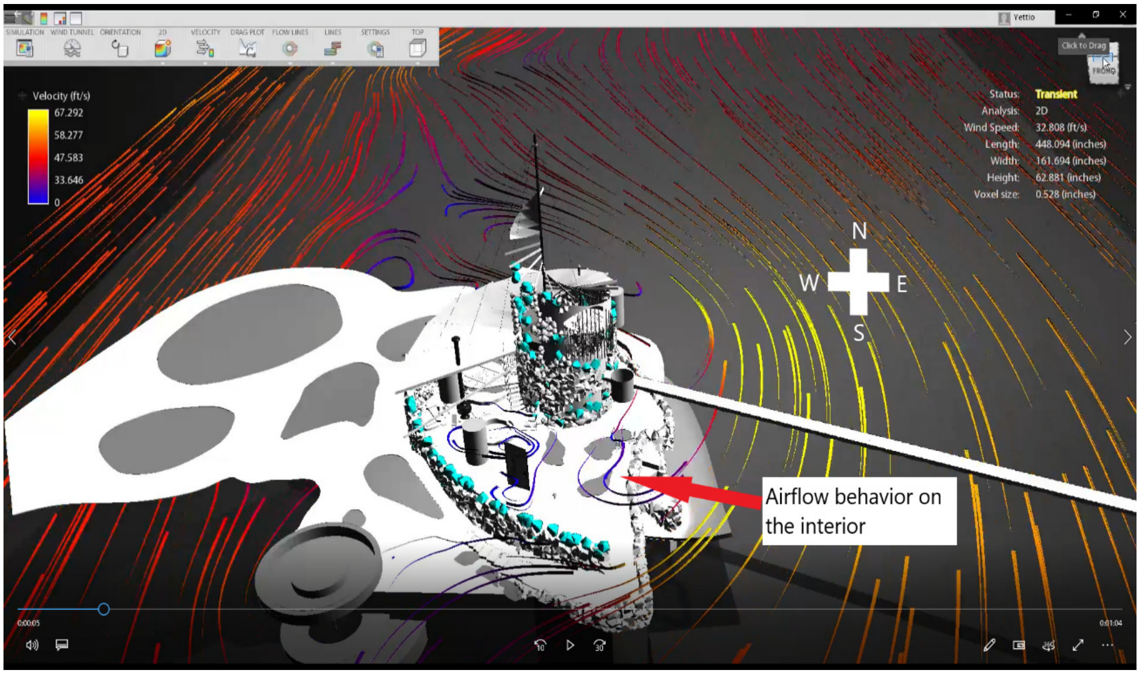


Figure 25- South air flow behavior on the Bavinger's interior.

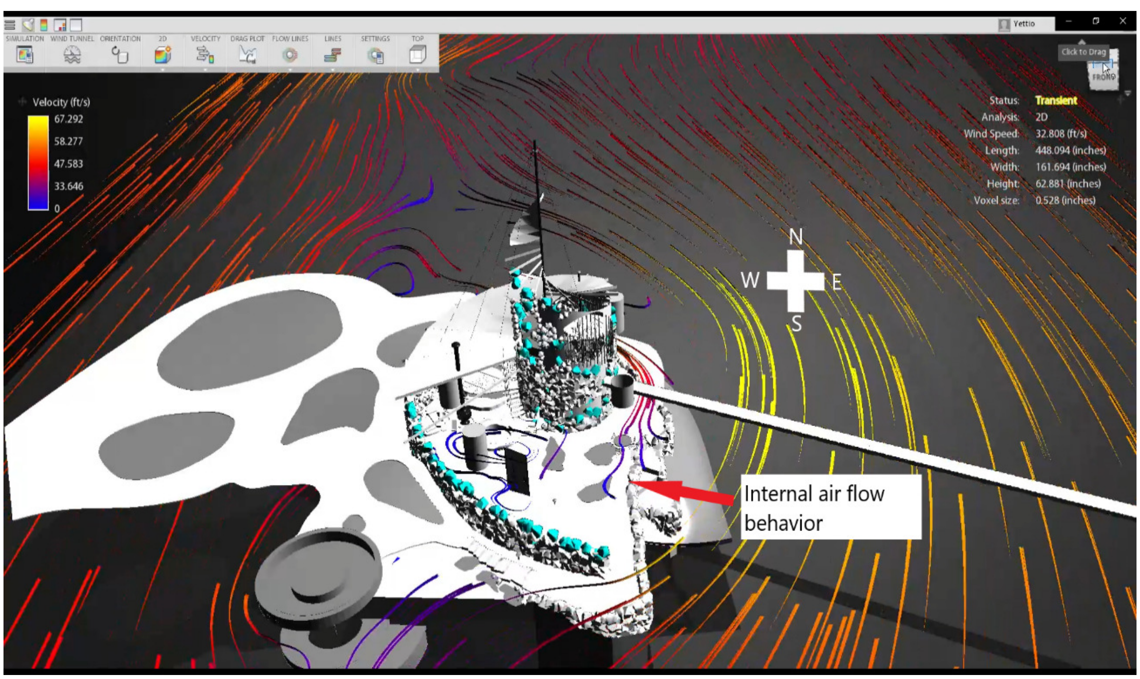


Figure 26- South air flow behavior on the Bavinger's interior.

4.4.2 Flow Line Analysis

From the images above, it can be viewed that the flow lines within the interior exemplify erratic and turbulent behavior. The flow can be seen moving throughout the bottom portion of the model. There is also no specific pattern to the flow lines, however, the flow is very apparent within the structure.

The air flow in figures 24 through 26 can be seen coming from the south and flow outside of the house maintains its speed.

4.4.3 Seasonal Correlation

The following observations were made. The direction of the structure was maintained throughout each season, with the apex facing south.

In testing the wind tunnel using the speeds of the winter and fall seasons, data from table 6 was taken and ran through the CFD software. Had the site been actually built in this direction, air flow would have entered the house at a high rate, however, maintaining a comfortable climate during these two seasons specifically, would have been very difficult.

During the spring and summer seasons, wind speeds were generally lower, thus giving a benefit to the orientation of the site during the wind tunnel testing. Since more airflow enters the interior at this position, cooling the house during the hotter months would have worked fairly well in comparison to the site having the apex positioned in the northern direction.

4.5 Wind Flow- North

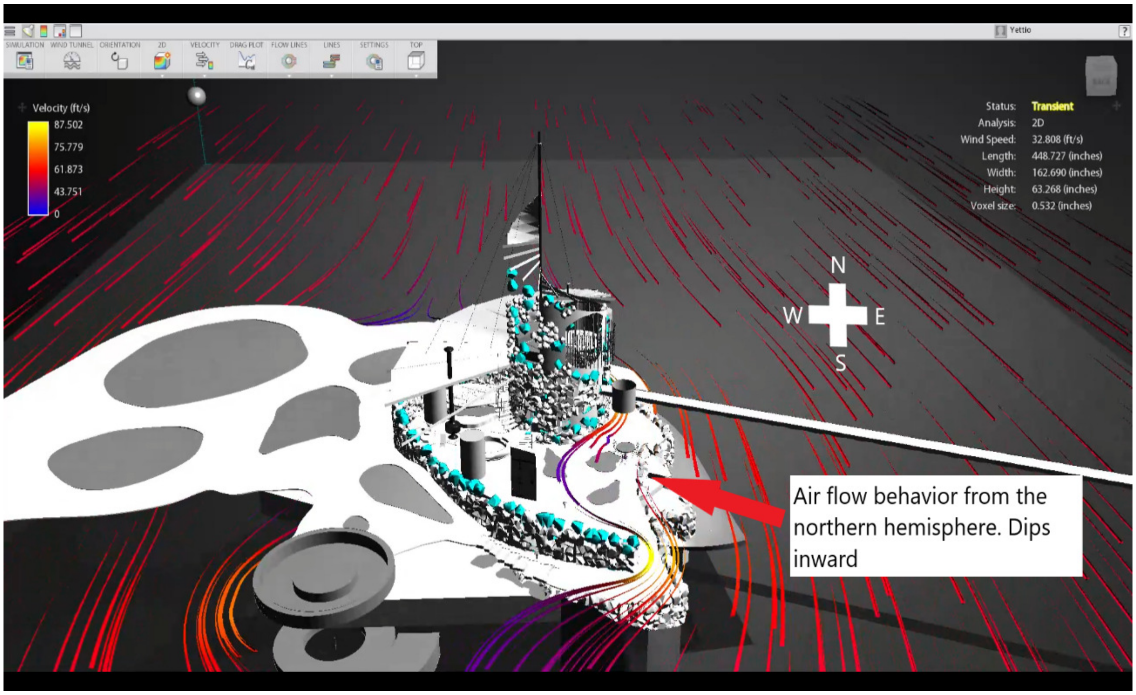


Figure 27- Winds coming from the north with the apex facing the north (correct orientation).

The model was rotated and oriented in the same direction as documented in figure 3. This orientation of the model is in fact the correct position of the house. Results were achieved by rotating the model by 180 degrees on its z-axis to account for the wind blowing from the north. This rotation was done in order to orient the model horizontally with the flow lines.

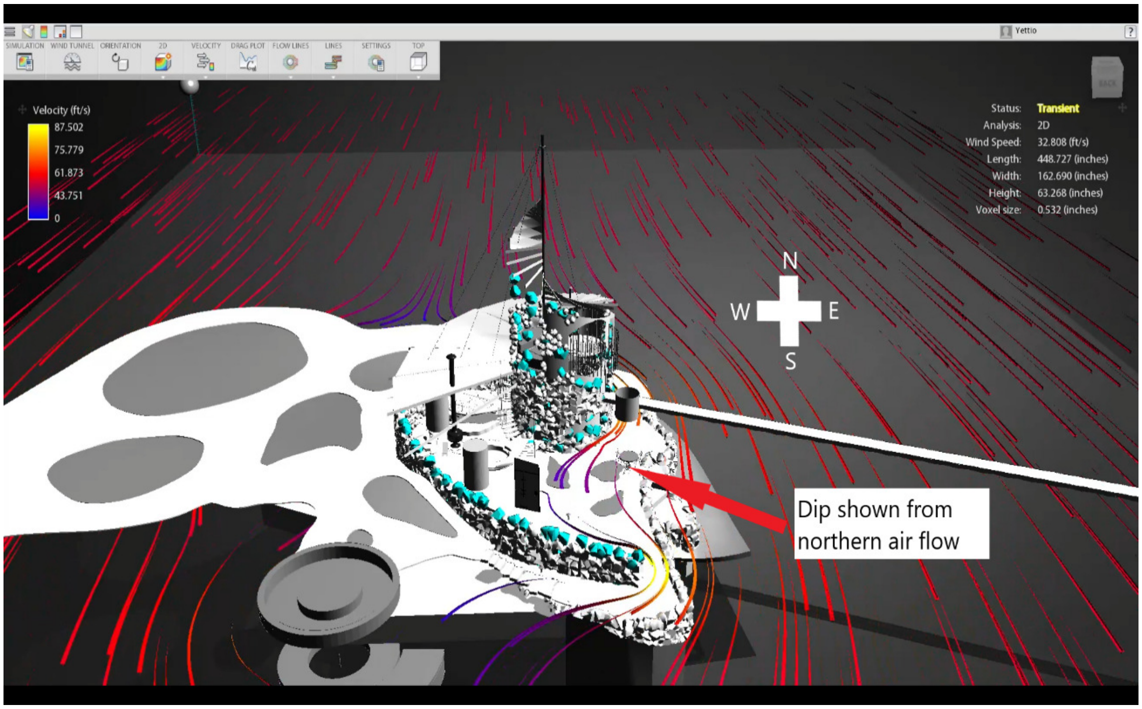


Figure 28- Winds coming from the north with the apex facing the north. Dips in the flow can be seen (correct orientation).

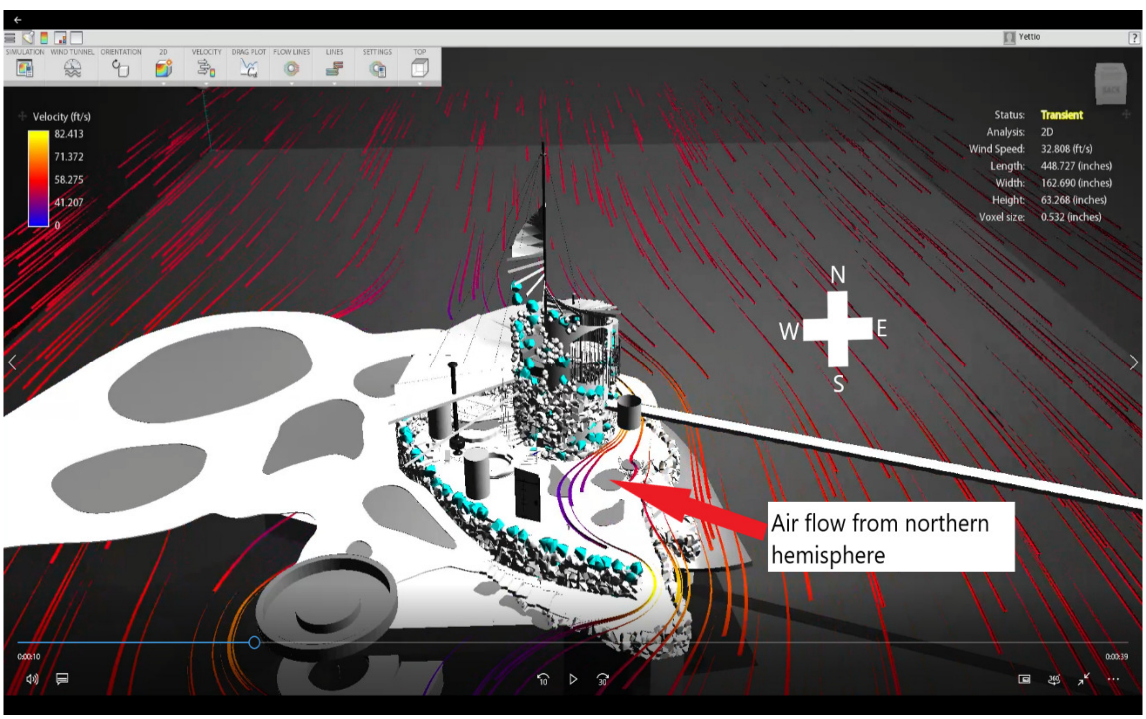


Figure 29- Winds coming from the north with the apex facing the north (correct orientation).

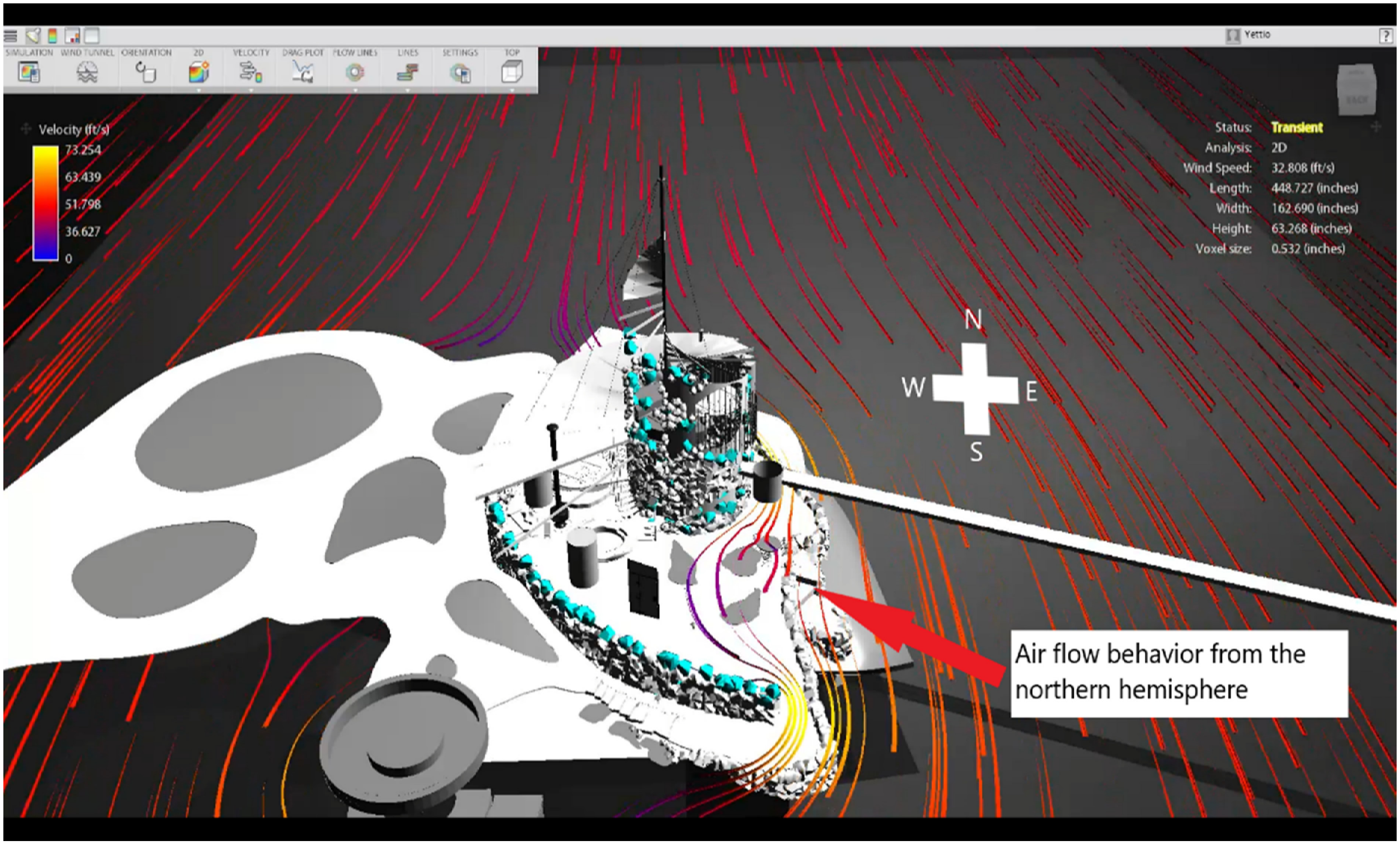


Figure 30- Winds coming from the north with the apex facing the north (correct orientation).

Using the data collected from Autodesk Flow, it was observed that the air flowing form the north with the apex facing north, provided a much more suitable ventilation scenario compared to the airflow from the south. In figure 27 through 30, flow lines can be viewed dipping into the corner where the door and large window are located. The color of the flow lines varies between purple and blue. This signifies that the rate of this air flow is slowed, but maintained when coming into contact with the interior of the house.

During the winter and fall seasons, the wind flow is predominantly blocked from entering the structure at a high rate. Unlike the erratic behavior from the wind testing using winds coming from the south, the flow on the internal area of the model is much more controlled. Specifically, during the fall, wind speeds increase by almost 10 miles per hour overall, and in the November and December months, the air flow maintained those speeds. It is important to note that the relative humidity during the fall season jumps significantly in the month of September. The humidity is over 70 percent for most of the fall and majority of the winter. This means air cooling using evaporation was likely very low. This was to be expected from the data, as the wind speed, direction and season of the year reflect a higher need for heating the space, rather than cooling it.

During the spring and summer seasons, the relative humidity rarely went about 70 percent, according to the Climate Consultant data. This would allow for some natural ventilation to take place despite the flow characteristics. This type of ventilation was more often than not due to evaporation of the air over the water garden.

5 Discussion

The Bavinger house site was analyzed and tested in a wind tunnel to view the natural ventilation behavior. This was first done by assessing components of the site that assisted in natural cooling (i.e. passive cooling) and by also documenting the wind patterns during each month of the year. These wind speeds were then grouped by season- along with the wind direction- and were input inside the wind tunnel software to simulate how the circulation of the air would behave with the apex facing south verses north.

5.1 Conducive Results

It was discovered that the site was placed 180 degrees from the original site plans, and this was further reinforced by overlaying the site plans found onto a google map image that predated the site. This in turn worked with the wind speeds and directions that passed through the site, by blocking harsher colder winds in the winter and utilizing the influx of wind on the site during the summer. The passive cooling methods Goff employed on the house through his design, also worked with each other in cooling and ventilating the house. These findings are significant in furthering the study of Bruce Goff's approach to architectural design as well as his understanding of engineering implementation. The findings also support the theory that Goff, being largely self-taught, had a variably thorough understanding of how to best mesh science, engineering, and nature into his designs. Lastly, the results give more insight to the systems of the Bavinger house since it is no longer standing.

5.2 Non-Conducive Results

The sectioning of the Bavinger house into intervals was distorted due to the 3D model file being extremely large. In parts throughout the file, the 3D mesh was not fine enough to allow for the flow lines to properly move through the model during testing. Portions of the rock wall and glass cullets that were included in the model were also distorted during sectioning (which is apparent throughout the partial model images from the wind tunnel testing), as the original software used to create the model was not available for use in correcting the design. While testing the north wind flow, pockets in the model created blue flow lines in the interior of the structure. These flow lines were negligible in regards to affecting the data.

These limitations of the study and the research software that was available prohibited the observation of finely detailed internal circulation patterns. Had the 3D model been corrected from distortion or implemented in a different CFD program, the flow line patterns could have moved more fluidly within the wind tunnel. Closer observation of the internal circulation behavior would have also been a possibility, and circulation patterns spiraling up and out through the apex of the Bavinger house would have likely been viewable.

6 Recommendations

For this research, it is recommended that further wind analysis is continued with stronger CFD software. In order to test how the wind circulated upwards through the interior of the house, a model with finer mesh detail would need to be created, or the current model would need to be adjusted to allow for proper air flow behavior to be viewed.

Further site analysis of the original plans would be beneficial in uncovering more unknown ventilation techniques or processes. Access to these files would need to be obtained from the Art institute of Chicago, however, as many of Bruce Goff's sketches, plans and designs reside there, and are only available with limited access.

To further support the hypothesis that Goff was intentional about his passive ventilation on the Bavinger house, these constituents would need to be further uncovered.

7 Conclusions

The site layout of the Bavinger house was one of the most important factors in influencing air flow throughout the structure. Had the site layout of the Bavinger house been placed with the apex facing the west, the entrance would have thus been facing the north. This would have created erratic wind flow and circulation into the side with the entrance, and air cooling the house during warmer months would have been much more effective. Maintaining a comfortable climate throughout the year and changing seasons would have been a difficult act, however. The colder winds in the fall and winter would have acted against the site layout, and any solar energy captured by the windows would have been minimal, since few windows would have been facing the east and west.

If the site layout was constructed like that of the plan drawings, with the apex facing south and the tail end of the design facing north, colder wind temperatures would have routinely entered the house during the fall and winter seasons. The ponds located on the interior of the ground level would have likely created colder drafts, causing the occupants of the house to work harder to keep the house warm in the winter.

The method of construction and materials were not only cost effective, but they also worked to implement a passive ventilation system that aided in cooling the house. Whether or not this was intentional, it can be concluded that the investigated elements of the site positively contributed to ventilating the house.

Utilization of these passive techniques and methods should be revisited and studied more. The use of HVAC systems, though beneficial, is much more expensive then implementing passive design. HVAC systems also create rigidity in temperature and human comfort levels. In order to create a ventilation system that benefits both humans and the natural environment, the integration of passive ventilation techniques like that of Goff's, and mechanical ventilation methods of today should be further pursued.

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